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# ADVANCED LIFE ANALYSIS METHODS - Cracking Data Survey and NDI Assessment for Attachment Lugs

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This technical report has been reviewed and is approved for publication.

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Results of a survey of cracking data and an evaluation of NDI capability for aircraft attachment lugs are presented. This survey and evaluation are part of an overall effort involving fatigue testing and analyses to develop the design criteria and analytical methods necessary to ensure the damage tolerance of pin-loaded lugs. Cracking data from coupon and full scale fatigue tests and from service failures are summarized in terms of causes of initial cracking and final failure; initial crack type, shape, location and multiplicity; and final critical crack size. Existing NDI capability is reviewed, and an inspectable initial flaw size criterion for lugs is proposed, subject to experimental verification. Originator furnished keywords include:-

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## FOREWORD

This is Volume I of six final report volumes on Contract F33615-80-C-3211, "Advanced Life Analysis Methods." The work reported herein was conducted jointly by Lockheed-Georgia Company and Lockheed-California Company under contract with Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB. J.L. Rudd is the Air Force project leader.

The authors wish to thank W. H. Sproat and M. J. Berg for their advice and assistance in the NDI evaluation, and J. M. Cox and S. E. Wallace for their technical assistance in gathering and compiling the service cracking data.

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# SECTION I

## PROGRAM SUMMARY

The objective of the program is to develop the design criteria and analytical methods necessary to ensure the damage tolerance of aircraft attachment lugs. As planned, the program proceeds logically from an extensive cracking data survey and nondestructive inspection (NDI) assessment, through method development and evaluation, to the preparation of damage tolerance design criteria for aircraft attachment lugs.

The program consists of three (3) phases involving seven tasks. Phase I consists of Tasks I, II and III; Phase II consists of Tasks IV, V and VI; and Phase III consists of Task VII. A roadmap shown in Figure 1-1 summarizes the major activities by task, decision points and their interrelationships.

Task I involves a survey of structural cracking data such as the initial flaw size, shape and location which occur in aircraft attachment lugs. Sources for these data include open literature, available Lockheed data, and visits to the five Air Force Air Logistics Centers (ALCs). The types of aircraft structure used to obtain these data include service aircraft, full scale test articles, component test articles, and coupon specimens.

Task II assesses the current NDI capability to find these flaws or cracks. This assessment is to be based upon information obtained from the open literature, available Lockheed NDI data and experience, and Air Force ALC data. The NDI techniques capable of finding flaws in attachment lugs and the flaw sizes these techniques are capable of finding are identified. Where possible, the probability of detecting a flaw of a particular size for the NDI technique involved are specified as well as the confidence level assigned to that probability. The results obtained from Tasks I and II will be used in the formulation of the initial flaw assumptions to be developed in Task VII as part of the damage tolerant design criteria for attachment lugs.

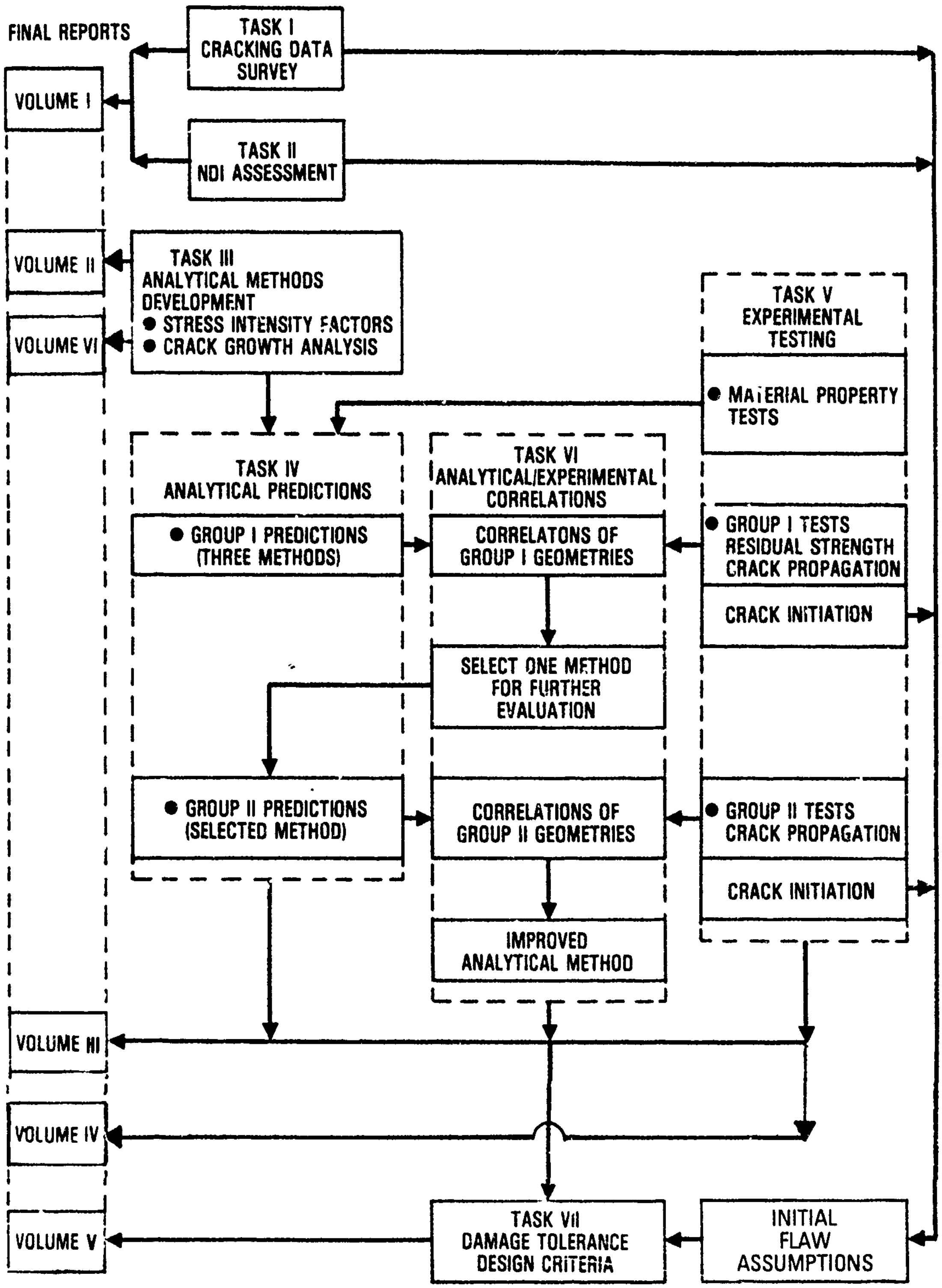


Figure 1-1. Roadmap of the Program

Task III involves the development of three different levels of complexity and degrees of sophistication for determining stress intensity factors for single corner cracks and single through-the-thickness cracks in aircraft attachment lugs, and the development of crack growth analyses capable of predicting the growth behavior of these cracks and residual strength of these lugs. These stress intensity factors and crack growth analyses are used in Task IV to predict the residual strength and the crack growth behavior for a number of different geometries and test conditions defined in the experimental program. These predictions are made prior to testing. Two groups of attachment lug geometries are tested and experimental test data are generated in Task V. The analytical methods developed in Task III are evaluated by correlating the analytical predictions made in Task IV with the Group I experimental test data generated in Task V. These correlations are used to select one method (based upon accuracy and cost) for use in prediction for Group II tests. Further evaluation of the selected method is made by correlating the analytical predictions for the Group II tests (Task IV) with the experimental test results (Task V). These correlations indicate what improvements are necessary for the selected analytical method. The results are presented in parametric format useful to designers and analysts. Damage tolerant design criteria for aircraft attachment lugs are developed in Task VII. These criteria are similar in nature to those of Military Specification MIL-A-83444, and require crack growth analyses by the types of methods developed and verified in Tasks III through VI. The criteria include initial flaw assumptions (e.g., initial flaw type, shape, size, etc.) based upon the cracking data survey of Task I, NDI assessment of Task II, and crack initiation tests of Task V.

As Figure 1-1 shows, the following sequence of final report volumes is generated under this project:

Volume I. Cracking Data Survey and NDI Assessment for Attachment Lugs

Volume II. Crack Growth Analysis Methods for Attachment Lugs

Volume III. Experimental Evaluation of Crack Growth Analysis Methods for Attachment Lugs

Volume IV. Tabulated Test Data for Attachment Lugs

Volume V. Executive Summary and Damage Tolerance Criteria Recommendations for Attachment Lugs

Volume VI. User's Manual for "LUGRO" Computer Program to Predict Crack Growth in Attachment Lugs

## SECTION II

## INTRODUCTION

A primary objective of this research contract is to provide guidelines for establishing damage tolerance design criteria for attachment lugs. To establish such criteria, a thorough definition of the initial damage population for lugs is essential. There are two aspects to the initial damage population: The question of what damage can and does occur, and the question of what damage can be found (and therefore deleted from the population). These two questions are addressed, respectively, in Tasks I and II of this research.

To obtain service cracking and NDI data on attachment lugs, visits were made to five Air Force Air Logistics Centers. The locations, dates and personnel involved in these visits are summarized in Table 2-1.

Hill AFB has exclusive responsibility for all depot-level overhaul maintenance on Air Force landing gears. The visit included a tour of the large, semiautomated maintenance facility. Discussion with one NDI expert provided a great deal of insight on NDI methods and capabilities. Extensive files of metallurgical failure analysis reports were made available. Copies were taken of 92 such reports on service cracking, 70 of which proved to be relevant to attachment lugs upon later examination.

McClellan Air Force Base seems to have an excellent reputation in the NDI field. Demonstrations were given of various NDI methods applicable to lugs and detailed information was provided, particularly for the magnetic rubber method for steel and automatic eddy current for aluminum. A small amount of service cracking data was obtained.

The visit to Kelly Air Force Base included a brief discussion of NDI capabilities as applied to lugs. Some drawings and reports were examined showing attachment lug applications, particularly in fighter aircraft wings. Copies of six relevant metallurgical reports on service cracking in lugs were obtained.

TABLE 2-1. VISITS TO AIR FORCE AIR LOGISTICS CENTERS

| Location | Date of Visit | Personnel Visited |
|---|---|---|
| Ogden Air Logistics Center<br>Hill AFB, UT 84406 | 22-23 June, 1981 | Phil Allen, Don Bucher, Fred Seppi, Paul Becker, Frank Zuech, Richard Swasey, Art Johnson, Dick Hansen |
| Sacramento Air Logistics Center<br>McClellan AFB, CA 95652 | 24-25 June, 1981 | Bill Sutherland, Mike Findley, Al Rogel, Don Bailey, Toi Shigekawa, Jim Glen, Bob Dahl, Clarence Larue |
| San Antonio Air Logistics Center<br>Kelly AFB, TX 78241 | 5 Oct. 1981 | Ken Barnes, Elmer Benson, Von Bashay, George Burkhardt |
| Oklahoma City Air Logistics Center<br>Tinker AFB, OK 73145 | 6 Oct. 1981 | Bob Meadows, Steve Houtari, Bob Lewis, Gaddis Gann, Gabriel Laibinis, Dave McBride, Carol Fisher, Alan Clark, Ronald Stevens |
| Warner Robins Air Logistics Center<br>Robins AFB, GA 31098 | 8 Oct. 1981 | Tom Christian, Bill Elliot, Norman Waninger |

Note: All visits attended by J.L. Rudd (AFWAL/FIBEC), T.M. Hsu (Lockheed-Georgia Company) and T.R. Brussat (Lockheed-California Company)

At Tinker Air Force Base, after a brief visit to the fatigue laboratory, a meeting was held with 9 representatives of the NDI department and various ALC projects, including for example the B-1, B-52, E-3A, and KC-135 aircraft. The discussion covered NDI methods and practical inspectability problems. Information was provided on design applications of lugs and some NDI data, but no service cracking data were obtained.

At Warner Robins ALC, meetings were held with personnel involved in damage tolerance analysis methodology, failure analysis and NDI. Copies of many metallurgical failure reports gathered by ALC personnel before the visit were provided, and another set of such reports were transmitted by mail after the visit. A total of 43 of these were ultimately judged relevant to this program.

In addition to the data obtained from these visits, cracking data on lugs were obtained from the open literature and from Lockheed-California and Lockheed-Georgia Company records. The summary and evaluation of cracking data are given in Section III of this report; the NDI assessment is provided in Section IV. Conclusions and recommendations from both tasks are summarized in Section V.

## SECTION III

## CRACKING DATA SURVEY

Damage tolerance design criteria for lugs can be similar in nature to those of the current Military Specification MIL-A-83444, "Airplane Damage Tolerance Requirements". The trends given in Table 3-1 are the basis for the initial flaw assumptions applicable to typical aircraft structure as given in MIL-A-83444.

Following the format of Table 3-1, a cracking data survey was undertaken to determine for lugs the typical (or most common) crack origins, locations, types, shapes, causes of growth, and multiplicity. In addition to determining the most common cases, the full variety of damage types that have occurred in aircraft lugs were reviewed.

Three different types of cracking data were reviewed: Coupon fatigue test data, mostly from the open literature; component and full scale test data, mostly from Lockheed-California and Lockheed-Georgia Company records, and service cracking data, from metallurgical records of Lockheed and the five Air Force Air Logistics Centers visited.

Lug coupon fatigue data from the literature have several advantages. The reported information is usually much more complete than the available information from service failures. Within one reference a number of similar tests are conducted, and thus the results can reflect significant trends rather than isolated cases.

On the other hand, the simplifications of geometry and loading conditions in lug coupons could possibly bias the data for some purposes. Therefore, test results were examined from some full-scale and component fatigue tests involving lugs.

Data from full scale and component tests also have their limitations. Since only fatigue results are reported, other causes of damage initiation and growth, such as corrosion, are unlikely to occur in these tests. Thus for example, information like statistical data on causes of lug failures can only be obtained from the actual service cracking data.

TABLE 3-1. MOST TYPICAL INITIAL DAMAGE FOR LARGE SCALE STRUCTURE (AS IMPLIED BY MIL-A-83444 SPECIFICATIONS)

| | |
|---|---|
| Origin: | Manufacturing or material defect |
| Location: | At a fastener hole, where tangential stress is maximum |
| Type: | Corner crack (or through-thickness crack for thin sheet) |
| Shape: | Quarter-circular (corner crack) |
| Cause of growth: | Fatigue |
| Multiplicity: | Mating structural members with a common fastener hole are often both cracked similarly |

Before the cracking data surveys were undertaken, a compilation was made of lug shapes used on three types of aircraft manufactured at Lockheed-California Company. The lug shapes are expressed in terms of the ratio of hole diameter to thickness, D/t, and the ratio of width to hole diameter, W/D. Figures 3-1 and 3-2 are probability plots of these data. The abscissa of these plots is the estimated probability that an arbitrarily selected lug from the same population as these 78 lugs will have a W/D (or D/t) ratio smaller than the plotted value. For example, Figure 3-1 estimates that the probability of D/t ratio being less than 1.0 is 10 percent. The 50 percent probability numbers are the median values for the 78 lugs surveyed. The median values of W/D and D/t are 1.785 and 2.0, respectively. Figures 3-1 and 3-2 are useful in that the usage regime of aircraft lugs is identified.

## 1. LUG COUPON FATIGUE CRACKING DATA

A study of the fatigue literature was conducted to examine the cracking behavior of attachment lug specimens. These data can be assumed to represent typical lug geometries, materials, and manufacturing qualities. High stress levels are used intentionally to cause fatigue cracks to grow, presumably from "typical" initial defects appropriate for durability analysis. The "rogue" defects appropriate for damage tolerance analysis may or may not be extensions of this "typical" defect population. In that sense, this study

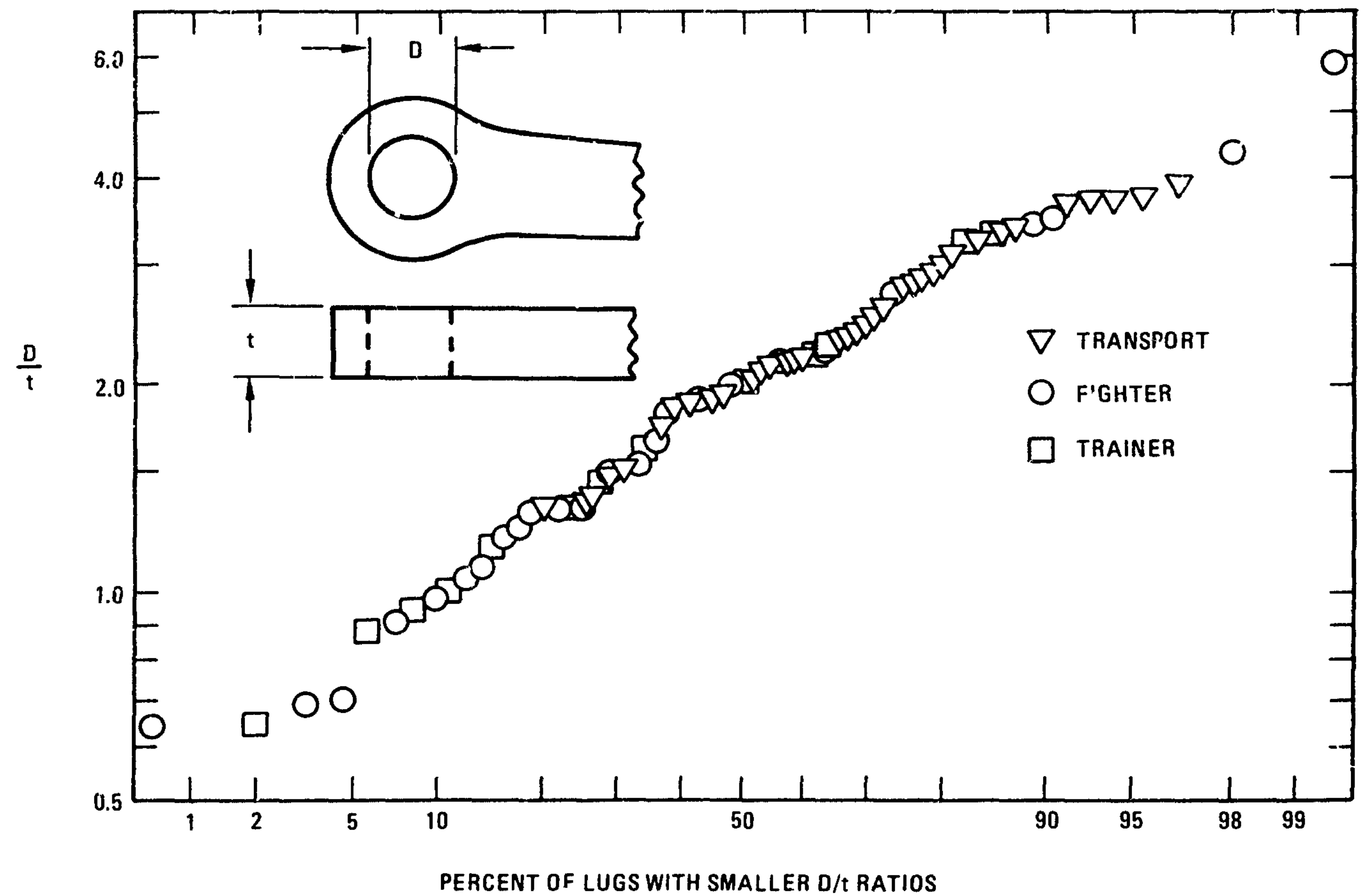


Figure 3-1. Survey of Hole-Diameter-to-Thickness Ratios for 78 Lockheed-California Aircraft Lugs

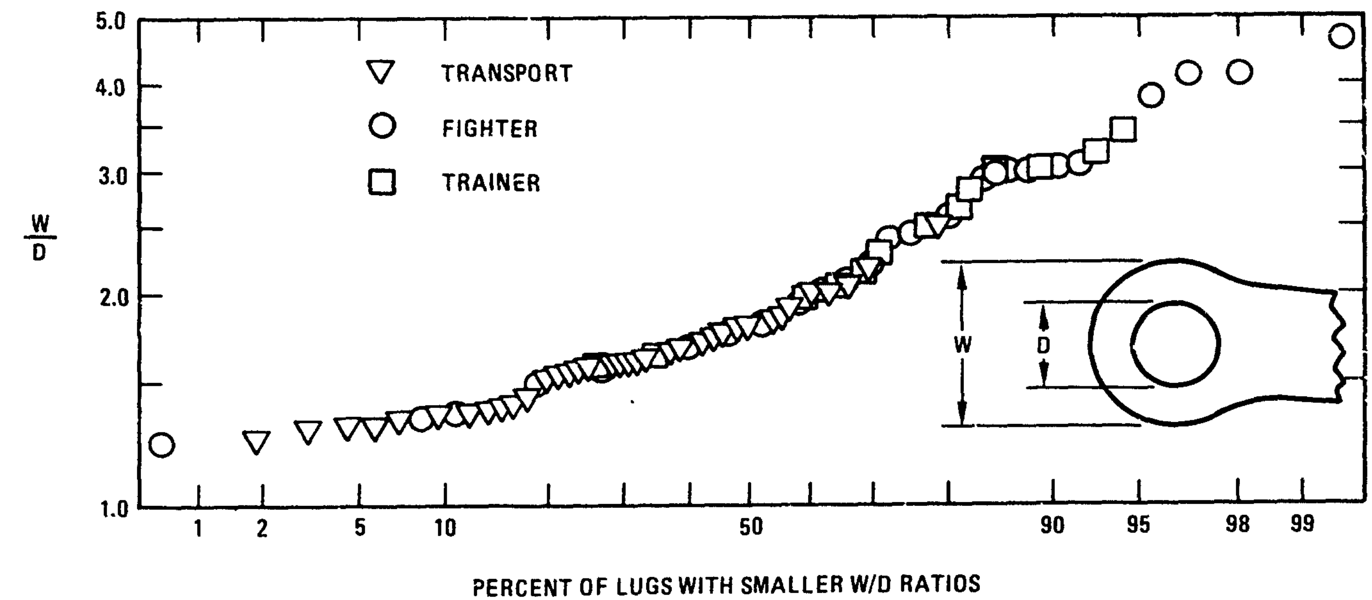


Figure 3-2. Survey of Width-to-Hole-Diameter Ratios for 78 Lockheed-California Aircraft Lugs

of fatigue test data may or may not provide relevant information about the nature of "rogue" defects in lugs.

In contrast to the usual emphasis on test lives, the focus of this study was upon the characteristics of the cracks. Thus, several references containing large quantities of fatigue life data on attachment lug specimens were of little or no use because crack characteristics were not discussed. This study covered crack multiplicity, type, shape, and location.

Kiddle [1] presents crack nucleation count results from 134 fatigue tests on lug specimens of four different aluminum alloys. The specimens were 0.3-inch thick with a hole diameter of 0.625-inch and a width of 1.6-inch. Thus, from Figures 3-1 and 3-2, the W/D ratio of 2.56 and D/t ratio of 2.08 are, respectively, wider than 80 percent of lugs but average in thickness. The pins had a 0.0006 to 0.0026-inch diametrical clearance in unbushed holes.

Examining the crack surfaces after testing, Kiddle finds a strong trend toward increasing number of flaw origins with increasing applied stress. The large pie chart in Figure 3-3 shows the number and type of crack origins that occurred on the "primary" crack side of the lug hole, the side with the larger final crack. Multiple crack origins occurred in more than two-thirds of the 155 specimens, with as many as 16 separate origins found across the 0.3-inch thickness. As the small pie chart shows, more than half the specimens had at least one corner crack origin. Data are very similar for the secondary (shorter) crack in Kiddle's lugs, Figure 3-4. It is noteworthy that all but two of the 155 specimens generated fatigue cracks on both sides of the lug hole during fatigue testing.

The clearance fit, unbushed condition of Kiddle's lug coupons probably magnifies the tendency for multiple cracking. Corner and surface crack origins were both common, but ultimately the crack type resulting from the coalescence of many crack origins would be a through-the-thickness crack.

Schijve and Hoeymakers [2] present data showing that natural cracks in lugs grew more slowly than artificially-induced cracks of equivalent size and

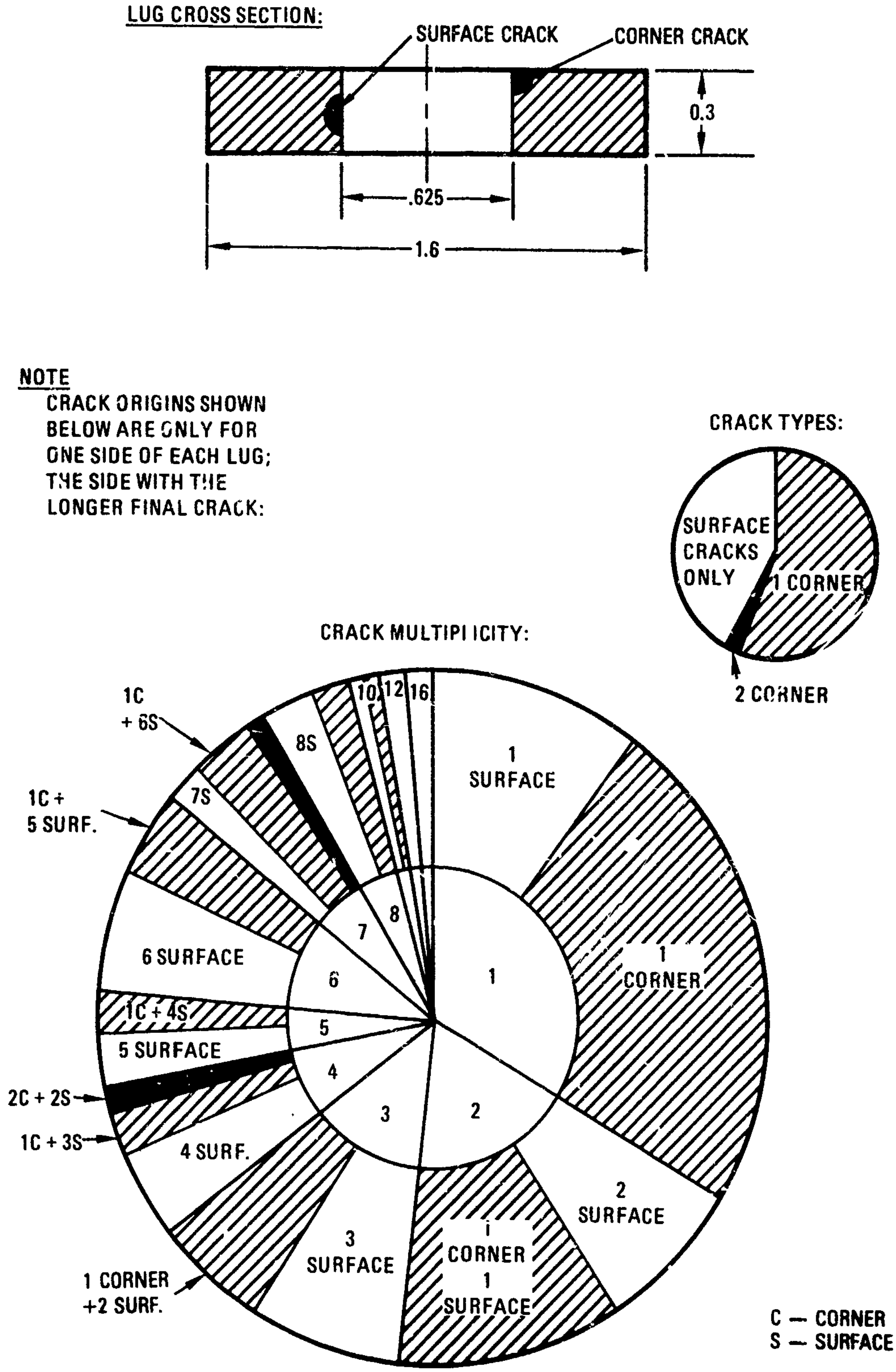


Figure 3-3. Number of Origins of Primary Crack, 155 Lug Coupons (Kiddle [1])

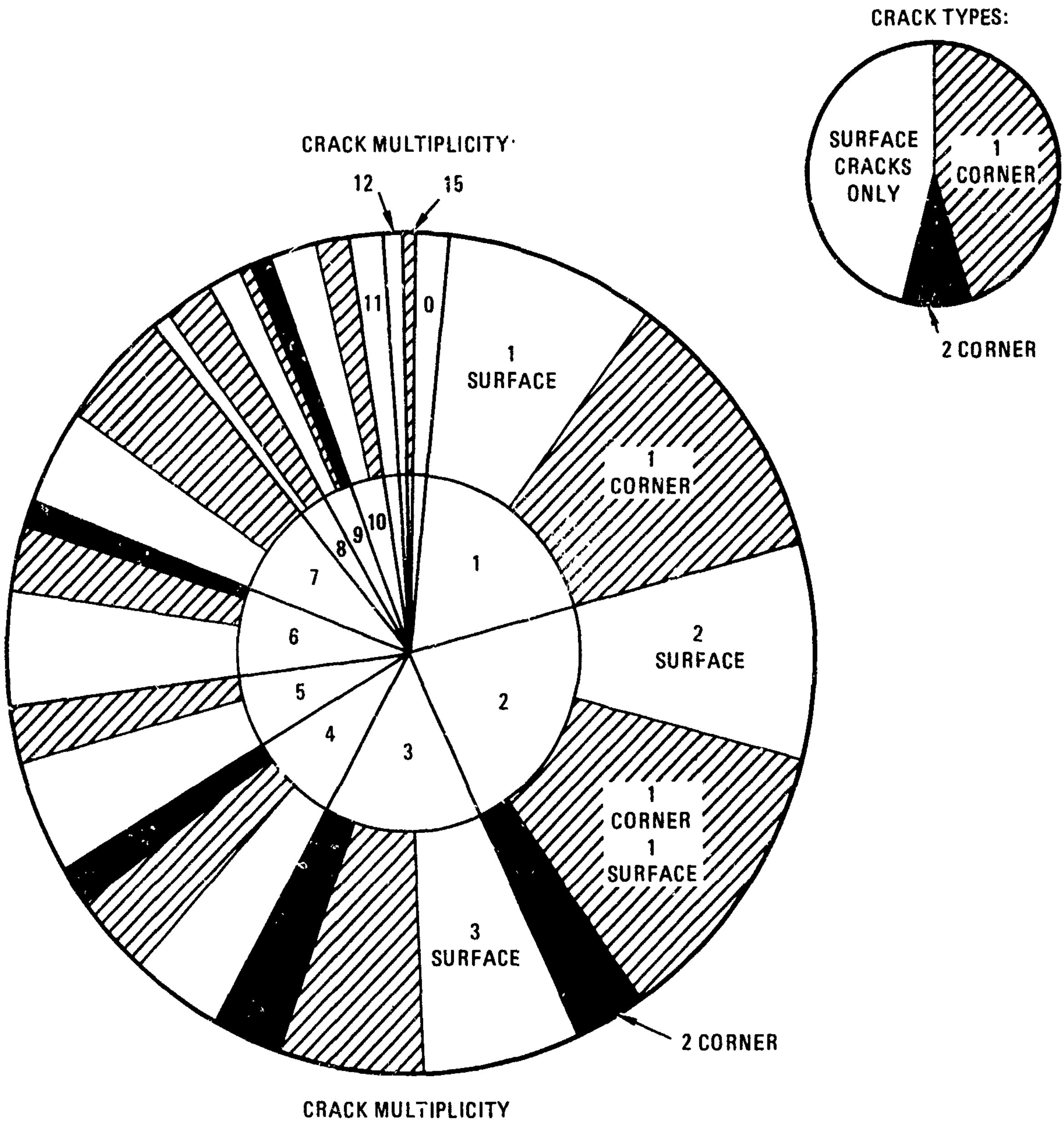


Figure 3-4. Number of Origins of Secondary Crack, 155 Lug Coupons (Kiddle [1])

shape. They attribute this difference to an ill-defined crack plane in the case of the natural cracks, arising from multiple, non-coplanar crack origins, acting to confound and thereby retard the growing crack. Their conclusion suggests that multiple-origin cracks may not be as critical as one would otherwise expect.

However, another explanation for the slow growth is plausible. Even when the cracks in [2] are longer, and therefore beyond the neighborhood of the origins, the natural cracks continue to grow more slowly than artificially-induced cracks. It is questionable to trace these rate differences for longer cracks to differences localized at the crack origin. On the other hand, the buildup of fretting deposits on the pin of a lug can alter the pin load distribution, reducing the stress intensity factor and thereby causing slower crack growth. It seems reasonable that fretting deposits built up while initiating the natural cracks in [2] could have impeded subsequent growth, compared to an artificially induced crack having no prior cyclic history. Thus, it remains to be determined whether multiple origins lead to slower crack growth in the manner suggested by Schijve and Hoeymakers.

Constant amplitude fatigue test results on lugs similar in geometry to those of Kiddle [1] are reported by Ghena [3]. Although multiple crack origins occurred and were mentioned, they were not systematically reported. However, the crack types (corner, mid-thickness surface, or near-corner surface cracks) in the bore of the hole were recorded for the dominant fatigue cracks leading eventually to failure in the 58 specimens. As Figure 3-5 shows, corner cracks and surface cracks were about equally common in these tests. The pins were close-tolerance clearance fit, as in [1].

Corner cracks are to be expected if there is out-of-plane bending of the lug or pin. Pin bending occurs most readily with hollow pins or long, thin pins (low D/t ratios).

Mann, et al., [4] report results of 16 constant amplitude and 4 simple programmed-loading fatigue tests on 1.25-inch thick lugs with 0.75-inch pins. This D/t ratio of 0.6 is lower than any of the 78 service lugs surveyed in Figure 3-1. Pin bending and a propensity for corner cracks would be expected.

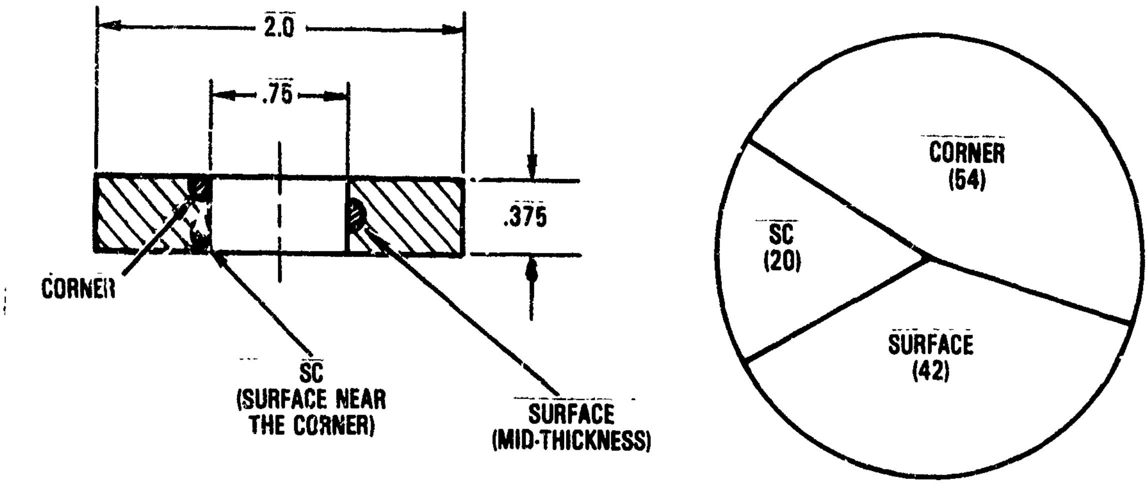


Figure 3-5. Crack Types for Dominant Fatigue Cracks (Ghena [3])

Multiple corner cracking dominated the behavior in the 16 constant amplitude tests. Four specimens were tested at each of four stress levels. Each specimen had a lug hole at either end, so when one end failed, the other end had cracking present also. After residual strength tests of the unbroken ends, 32 fracture surfaces could be examined for fatigue cracks. The four classes of cracks observed are sketched in Figure 3-6. These are corner cracks (C); semicircular surface cracks with the crack centerline within 0.1 inch of the corner (SC); semicircular surface cracks within the hole bore (S); and shallow surface cracks (SS). As the large pie chart shows, 71 cracks were corner cracks and 17 were near-corner cracks. There were no type-S or type-SS cracks produced by constant amplitude loading.

Thus, an average of 2.75 corner or near-corner cracks occurred for each of the 32 lug ends subjected to constant-amplitude loading. At the ends that failed in fatigue, there were at least two cracks in every specimen, and the average was 3.25 corner or near-corner cracks per lug.

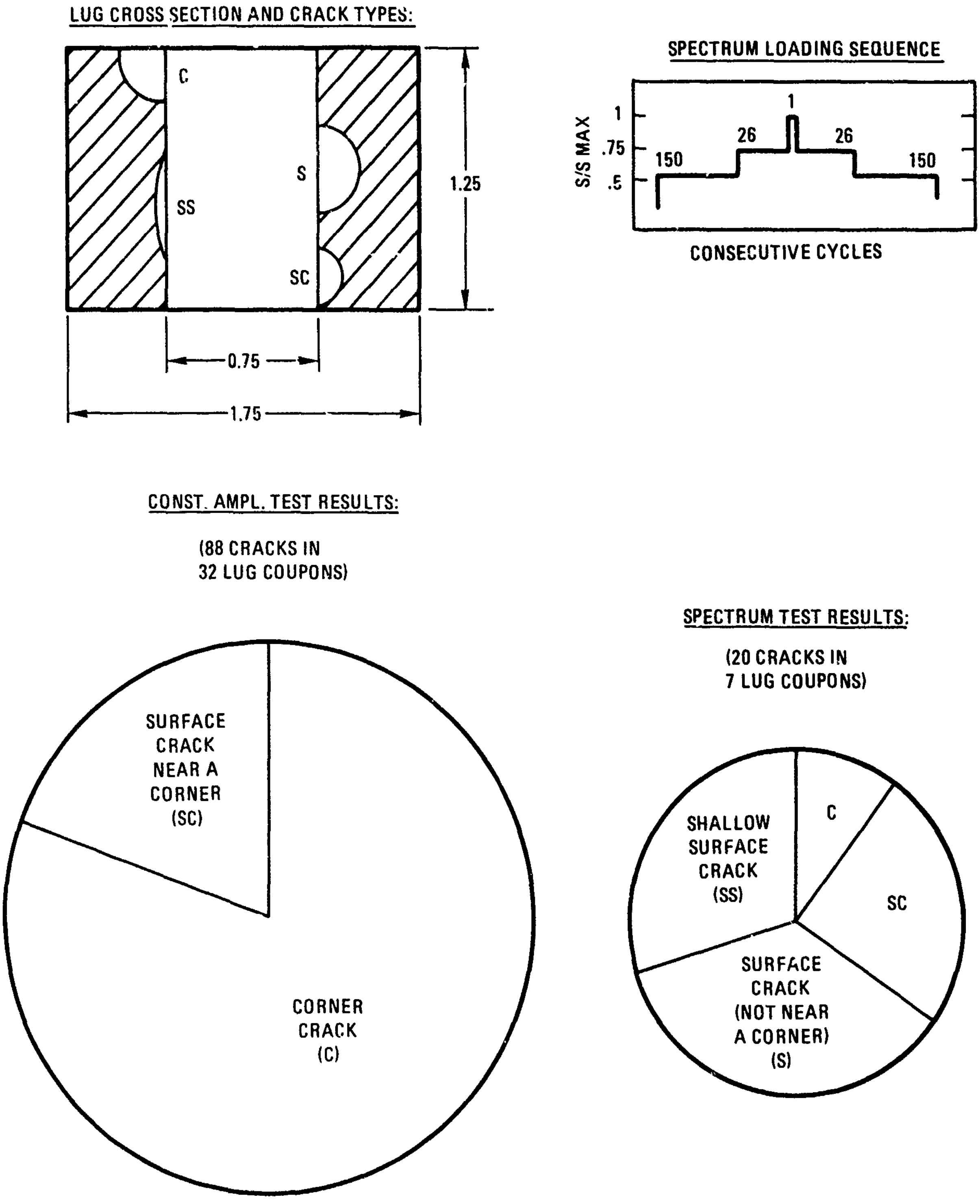


Figure 3-6. Crack Types in Thick Aluminum Lugs Under Constant Amplitude or Spectrum Fatigue Loading (Mann, et. al. [4])

The four spectrum tests involved a low-high-low sequence of the same stress levels as used in the constant-amplitude testing. As sketched in Figure 3-6, the largest stress level occurred only once per block.

The spectrum test results are shown in the smaller pie chart in Figure 3-6. In contrast to the cracks in the constant amplitude test specimens, only 2 were corner (C) and 5 were near-corner (SC) cracks, out of 20 total cracks. Furthermore, the spectrum fatigue lives were much longer than would have been predicted by linear cumulative damage analysis using the constant amplitude test results.

The following is one possible explanation for the resistance to corner cracks in the spectrum-loaded specimens. Pin bending is a geometrically nonlinear phenomenon, and is disproportionately severe at the highest stress levels. It is hypothesized that by pin bending the largest spectrum load permanently crushed the external corners of the lug hole out of contact with the pin. As a result, the contact stresses for the subsequent, lower loadings were maximum at points inside the bore of the hole. The corresponding maximum tangential stresses occurred in approximately the same thickness plane as these maximum contact stresses and led to surface cracks inside the bore of the hole rather than corner cracks.

For cases in which corner cracks occur, guidelines are needed for estimating corner flaw shape. Figure 3-7 shows a probability plot for the 22 cracks larger than 0.1-inch deep along the hole wall in the residual-strength tested lug ends of Mann, et al. [4]. The crack depth-to-length ratios (a/c) range between 1.38 and 2.18, with an average of 1.76. Shallower fatigue-induced corner crack shapes were observed by Broek, et al. [5] in data covering two aluminum alloys and three lug thicknesses ranging from D/t = 1.25 to 5. These data are also plotted in Figure 3-7. The a/c ratios range from 1.13 to 1.49, with a mean of 1.32. Their results are confirmed by ten data points presented by Hoskin and Carey [6] for 7079-T6 Aluminum lugs with a D/t ratio of 2.65, for which the a/c ratio ranged from 1.15 to 1.76 with a mean of 1.38.

Knowledge of the crack orientation around the hole periphery is essential for properly locating the precrack in damage tolerance testing and analysis.

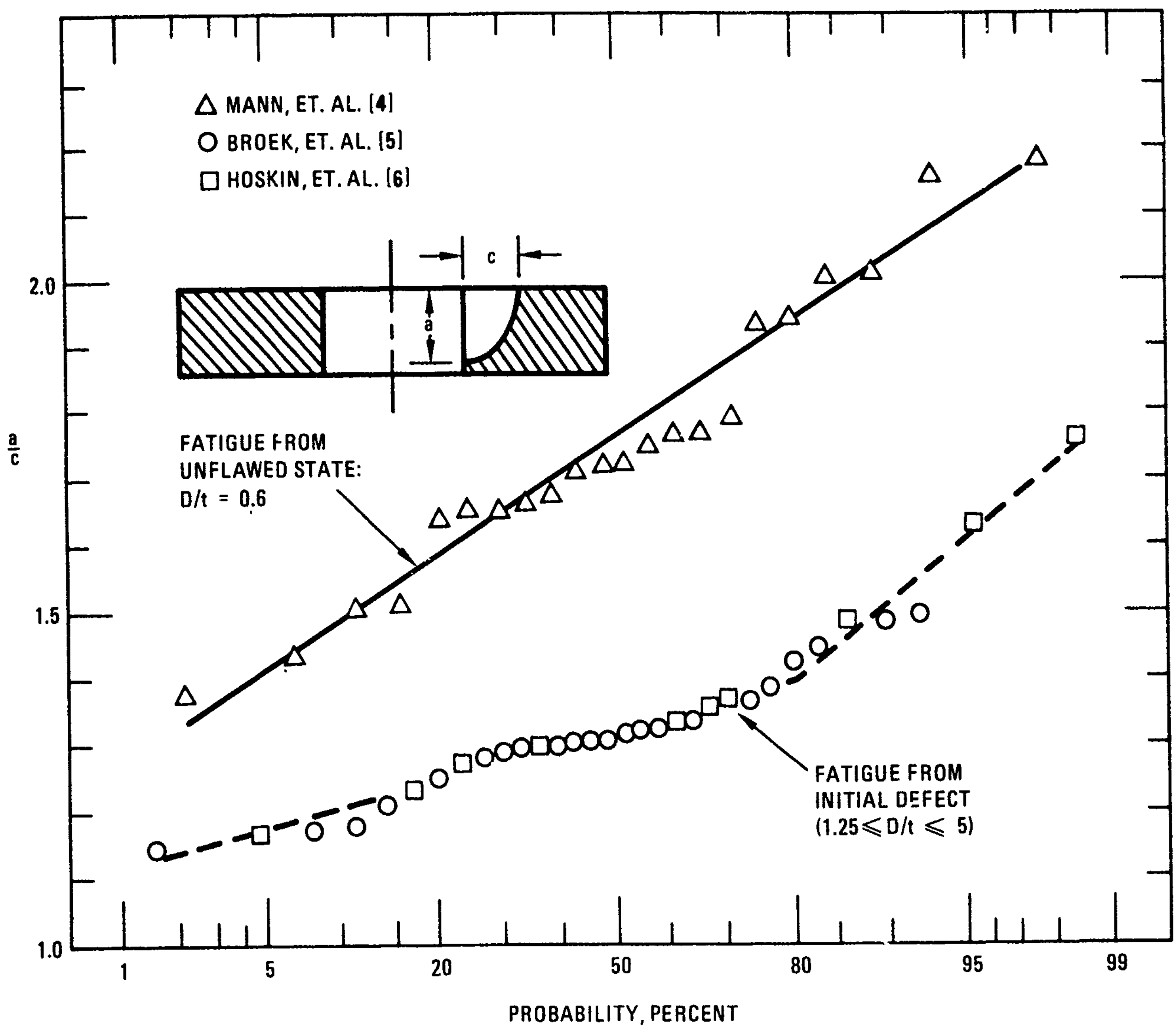


Figure 3-7. Corner Crack Shape in Lugs

Cracks might be expected to originate either near the location of the maximum tangential tension stress or near the critical fretting point where contact with the pin terminates.

Pin clearance or bushing interference can have a pronounced effect on crack orientation. Photos of three failed lug specimens are shown in [7]. The fatigue crack initiated at 119 degrees when an interference-fit pin was used; at 96 degrees for neat fit; and at 66 degrees for loose fit.

Test results from References [8] and [9] tend to confirm these trends. Thirty-five straight and tapered lugs with transition (neat) fit pins and axial loading cracked near 90 degrees [8]; while seven lugs with interference fit bushings and axial loadings cracked at larger angles, between 97 and 109 degrees [9].

In explanation, Schijve [10] points out that, as the pin interference increases, there is an increase in the angular positions of both the peak tangential stress and the critical fretting point at the edge of the zone of pin-bearing contact.

The fatigue test data of Larsson [8] clearly show the importance of the critical fretting point. Altogether, the crack positions for 142 cracks in lugs with transition-fit pins and no bushings are reported. For 14 cracks, all fretting within 60 degrees of the crack location was reported to be negligible. The other 128 cracks occurred within 10 degrees of the edge of a significant fretted zone. The pie chart of these data is shown in Figure 3-8, emphasizing the point that if fretting occurs, cracks nucleate near the edge of the fretted zone.

Lug pin pressure distributions were calculated by Callinan [11] using finite element analysis for various pin clearances and interferences. The results confirm the shift in the critical fretting point with pin fit, but also show a dependence on load magnitude. Figure 3-9 shows that for a bearing stress ratio of 0.0016 (corresponding to $\sigma_{br}$ = 16 ksi in an aluminum lug), the edge of the estimated pin contact arc shifts from 87 degrees for 0.3 percent clearance fit to 156 degrees for 0.4 percent interference. Note in Figure 3-10, however, that the arc of contact for either clearance or interference-fit pins

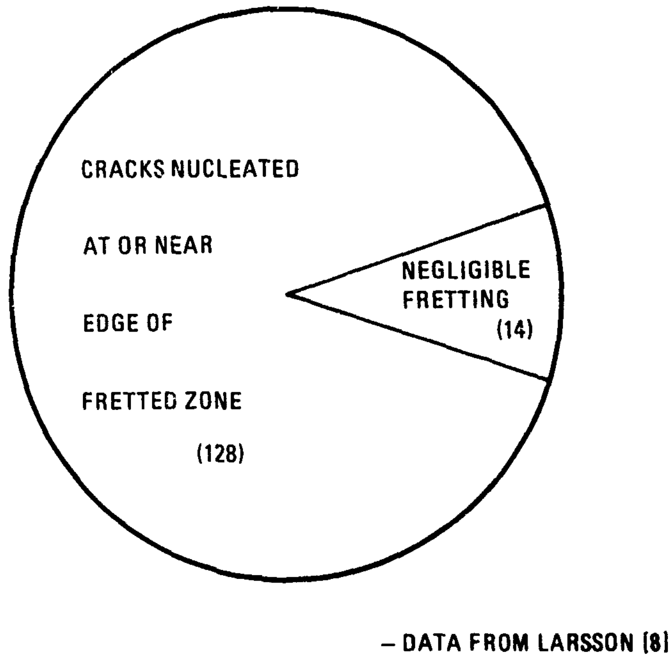


Figure 3-8. Correlation Between Crack Location and Edge of Fretted Zone

changes with load magnitude and approaches the arc of contact of a neat-fit pin as the load becomes larger.

When the pin is a neat-fit pin, the arc of contact is independent of load magnitude, so it doesn't shift during a loading cycle. Thus, for a neat-fit pin, the predicted arc of contact can readily be used to predict the critical location of initial fatigue cracks. Figure 3-11 shows a comparison of predicted and experimental cracking locations in a tapered lug with a neat-fit pin for various loading orientations. The test points are computed averages of data taken from [8]. The predictions of both the boundary of the pin contact arc and the location of peak tangential stress are from finite element analysis results from this program, reported in Volume II of the final report. The locus of points 90 degrees offset from the loading direction is shown for reference.

In summary, the following are concluded from the literature cracking data survey:

- Multiple-origin cracks on both sides of the lug hole are common when the lug has no preflaw and no compressive residual stresses due to

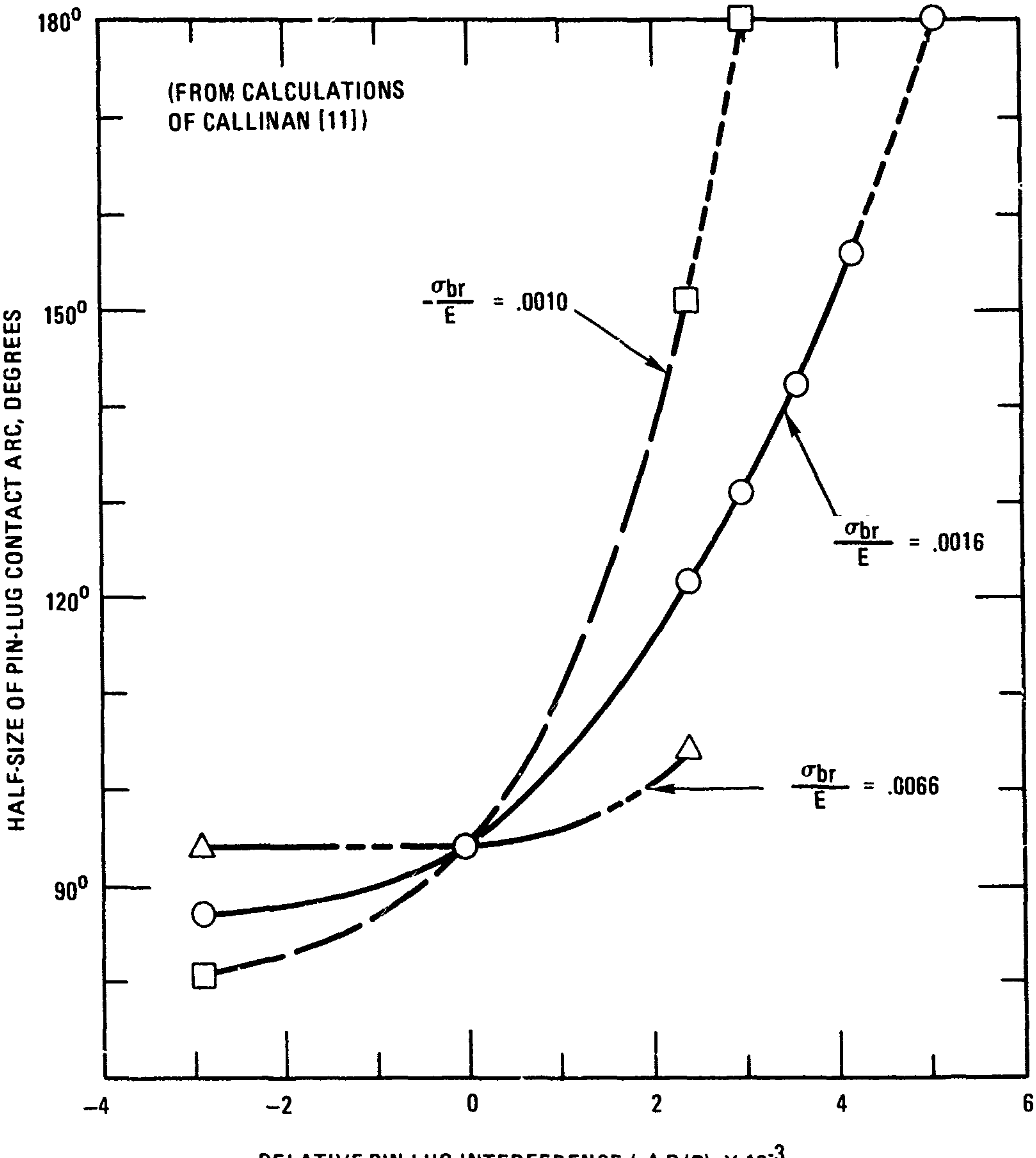


Figure 3-9. Dependence of Pin-Lug Contact Arc on Pin Fit

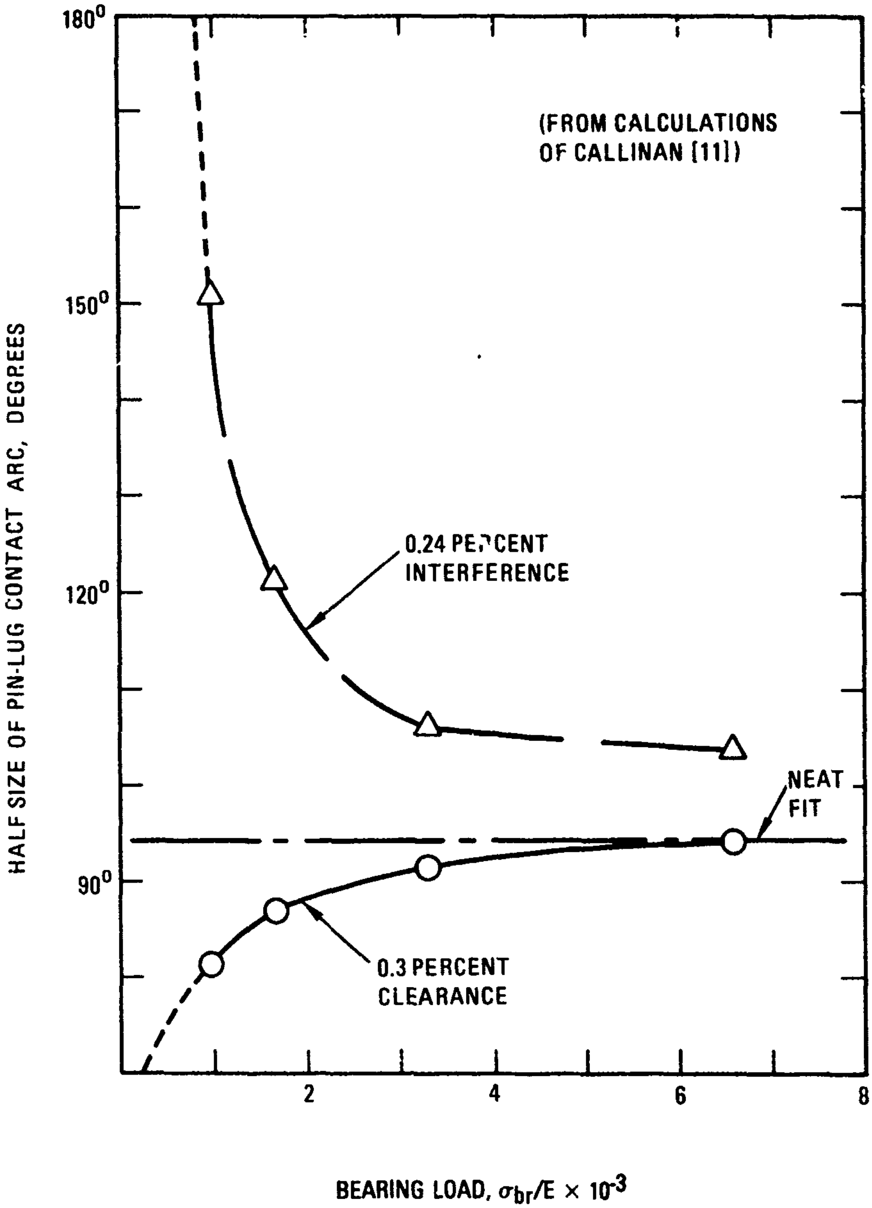


Figure 1-30. Dependence of Pin-Lug Contact Arc on Pin Load Magnitude

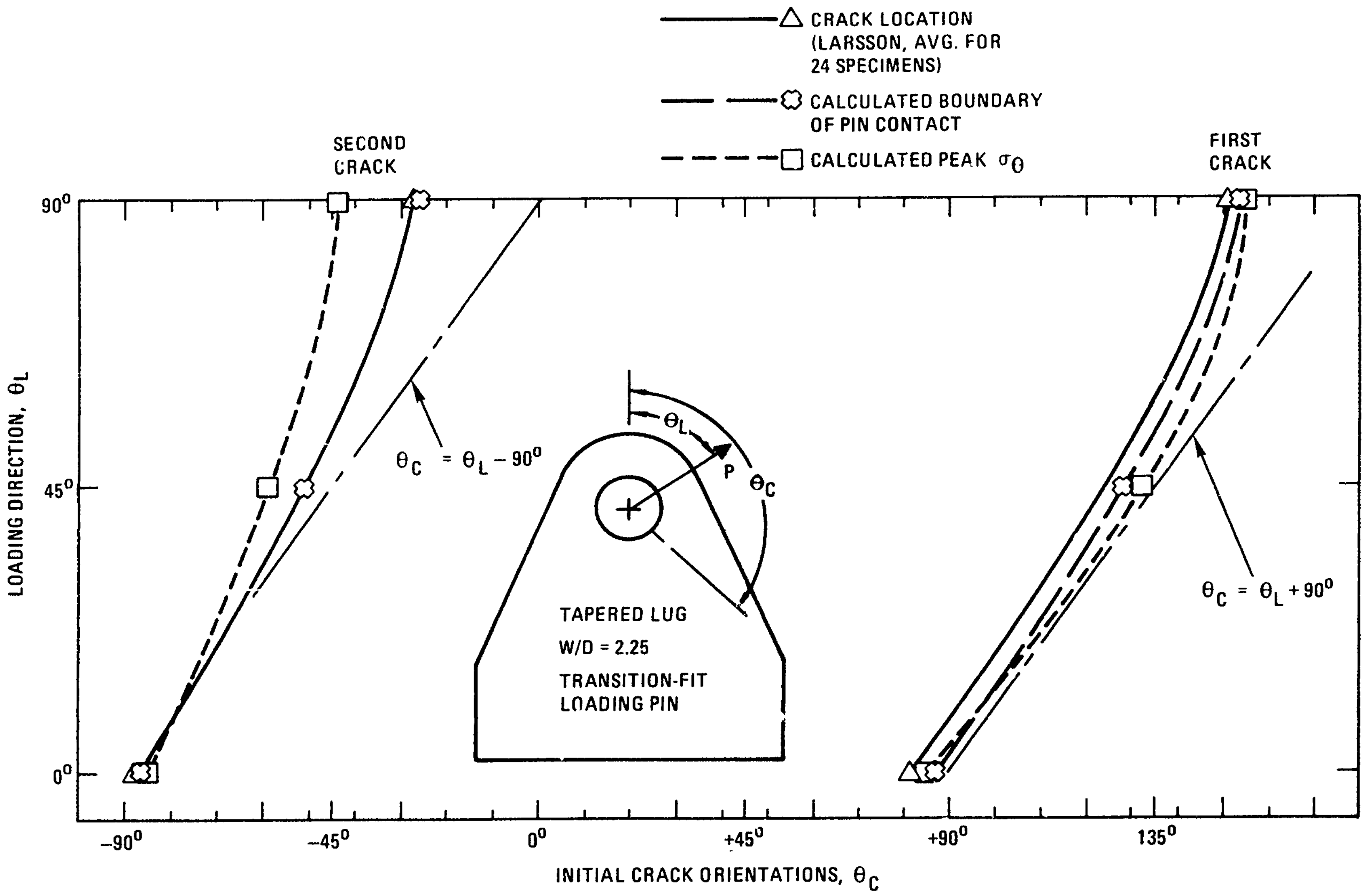


Figure 3-11. Experimental and Predicted Crack Locations for Various Loading Directions

shot-peening or interference-fit bushings. Multiple origins can lead to through-the-thickness cracks.

- Multiple corner cracks are common in constant-amplitude fatigue, particularly when pin bending occurs, such as when the pin is hollow or the D/t ratio is small. However, corner cracks appeared to be prevented by a retardation effect in the spectrum tests of [4], and instead, multiple cracks initiated within the bore of the hole.

- Corner cracks, when they occur, are consistently deep and quarter elliptic in shape. The typical ratio of the depth "a" to the surface length "c" is about 1.3 and perhaps higher.

- Crack location probably coincides with either the maximum tangential tension stress or the location of the edge of the fretting zone of contact. The first crack for loading at $\theta_L$ = 90 degrees to the lug axis tends to occur at a $\theta_c$ value of between 150 and 160 degrees from the lug axis; see Figure 3-11. These cracking angles tend to be smaller for clearance-fit pins and larger for interference-fit bushings, and may also be load-magnitude dependent.

## 2. SERVICE CRACKING DATA

A survey was conducted of service cracking data on attachment lugs from Lockheed and from the five Air Force Air Logistics Centers visited. All of these data were obtained from metallurgical failure analysis reports. These lugs that failed in service are but a small portion of the total population of lugs in service. Thus, these service cracking data represent the types of cracking problems for which damage tolerance criteria are needed. For that reason the data from this portion of the cracking data survey is the most relevant to establishing initial damage assumptions for damage tolerance analysis of lugs.

Each report was examined to ascertain whether the failure was relevant to the lug failure survey. Only failures through the pin hole were included in the survey; for example, cracking across the base of the lug remote from the lug hole was considered not relevant to this program, and such cases were excluded.

The data for each case were summarized on a form like the one exemplified in Table 3-2, and each was assigned a number. Statistical information on service cracking is summarized using the data summary format of Table 3-3, which is a tabulation of selected information taken from the Table 3-2 type forms. For each cracking case an "x" mark in these tables indicates the

TABLE 3-2. CRACKING DATA FOR LOCKHEED-GEORGIA COMPANY CASE NO. 7

# FAILURES THIS REPORT 1

DATA TYPE: In Service X : Component ______ : Coupon ______ :

MATERIAL/PRODUCT FORM: 7075-T6 Aluminum

PART DESCRIPTION: Door Actuator Support Bracket W = t = D =

LOAD DIRECTION/BENDING? ______

SURFACE PROTECTION/LUBRICATION/OIL HOLE: ______

BUSHING: Yes ______ : No ______ : Unknown ______ : Bushing Material ______

**CAUSE OF INITIATION:**

- Fretting ______
- Fatigue X
- Macroscopic Defect ______
- Tolerance ______
- Other ______

**CAUSE OF GROWTH:**

- Fatigue x
- SCC ______
- Static ______
- Other ______

**INITIAL CRACK TYPE:**

- Corner ______
- Surface (In Hole) X
- Surface (On Face) ______
- Internal Elliptic
- Flaw ______
- Other ______

**INITIAL CRACK SHAPE:**

- a/2c = ______
- Other ______

**CRACK PROPAGATION DIRECTION:**

- Radial ______
- Off Radial by ______ degrees
- Other ______

**CRACK ORIENTATION:**

- 1st Crack ______
- 2nd Crack ______
- Other ______

CRACK MULTIPLICITY: ______

REMARKS: ______

TABLE 3.3. SUMMARY OF LOCKHEED-GEORGIA COMPANY SERVICE CRACKING DATA FOR LUGS

| | Case Numbers | | | | | | | | | | | | | | | | | | | | Totals |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | |
| Material | | | | | | | | | | | | | | | | | | | | | |
| Aluminum | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | 19 |
| Steel | | | | | | | | | | | | | | | | | | | | X | 1 |
| Cause of Initiation | | | | | | | | | | | | | | | | | | | | | |
| Unknown | | X | X | X | | | | X | X | | | X | | | | | .7 | | | | 6.7 |
| Corrosion | X | | | | | | | | | | | | | | | | | | | | 1 |
| Static Overload | | | | | X | | | | | | | | | | | | | | | | 1 |
| SCC | | | | | | | | | | | | | X | X | X | | | | | | 3 |
| Mech. Defect | | | | | | | | | | | | | | | | | | X | X | | 2 |
| Assembly Stress | | | | | | X | | | | | | | | | | | | | | | 1 |
| Fatigue | | | | | | | X | | | | | | | | | | .3 | | | | 1.3 |
| Fretting | | | | | | | | | | | X | | | | | X | | | | | 2 |
| Crack in Anodize | | | | | | | | | | X | | | | | | | | | | | 1 |
| Quench Crack | | | | | | | | | | | | | | | | | | | | X | 1 |
| Cause of Growth | | | | | | | | | | | | | | | | | | | | | |
| Static Overload | | X | | | X | | | | | | | | | | | | | | | | 2 |
| Corrosion | X | | | | | | | | | | | | | | | | | | | | 1 |
| SCC | | | X | | | | | X | X | X | X | X | X | X | X | | | | X | | 10 |
| Fatigue | | | | X | | X | X | | | | | | | | | X | .3 | X | | X | 6.3 |
| Unknown | | | | | | | | | | | | | | | | | .7 | | | | .7 |
| Initial Crack Type | | | | | | | | | | | | | | | | | | | | | |
| Unknown | X | X | X | | X | X | | X | | | | | | | | | .7 | | | | 6.7 |
| Corner | | | | | | | | | X | | | X | | | | | .3 | | | X | 3.3 |
| Surface (Face) | | | | X | | | | | | | X | | X | X | X | X | | X | | X | 8 |
| Surface (Bore) | | | | | | | X | | | X | | | | | | | | | | | 2 |
| Bushing or Bearing | | | | | | | | | | | | | | | | | | | | | |
| Yes | | | | | | | | | | | | | X | | | | | | | | 1 |
| No | X | X | X | X | X | X | X | X | X | X | X | X | | X | X | X | | X | X | | 17 |
| Unknown | | | | | | | | | | | | | | | | | X | | | X | 2 |

material, cause of crack initiation, cause of crack growth, type of initial crack, and whether or not the lug hole has a bushing or bearing. For Case No. 17 in Table 3-3, seven failures were reported in one report, two corner crack-type fatigue failures and five failures of unknown origin. The numbers .3 and .7, used in place of the "x" marks in Table 3-3 indicate the proportions of each for Case No. 17.

Once reduced to the format of Table 3-3, the service cracking data could readily be studied statistically. A total of 160 separate metallurgical reports were found to be relevant, including 20 each from Lockheed-California and Lockheed-Georgia Companies, 70 from Hill Air Force Base, 43 from Robins Air Force Base, and 7 altogether from the other ALCs.

The following questions were considered during this data review:

- Is fatigue crack growth a major cause of service failures in lugs?
- What are the major causes of initial cracks in lugs?
- What are the most common types of initial cracks in lugs?
- Do the answers to the above depend upon the material of the lug, or on whether or not a bushing is used?

The emphasis being placed upon fatigue testing and analysis in Tasks III through VI of this program must be justified by showing that fatigue crack initiation and growth is a major cause of service failures of lugs. Figures 3-12 and 3-13 show the causes of cracking and causes of failure for the 160 service cracking cases surveyed, and give a breakdown of each for aluminum and steel lugs. The three most common causes of crack initiation and growth were found to be corrosion/stress corrosion cracking (35 percent for initiation and 36 percent for growth), fatigue/fretting (31 percent for initiation and 34 percent for growth), and static overload (21 and 26 percent). In aluminum, fatigue is the major cause of both crack initiation and crack growth, causing 32 percent of initial cracking and 37 percent of crack growth. In steel, corrosion/stress corrosion is the dominant cause of cracking, with fatigue/fretting the cause of crack initiation in 20 percent of cases and fatigue the cause of crack growth in the same percentage.

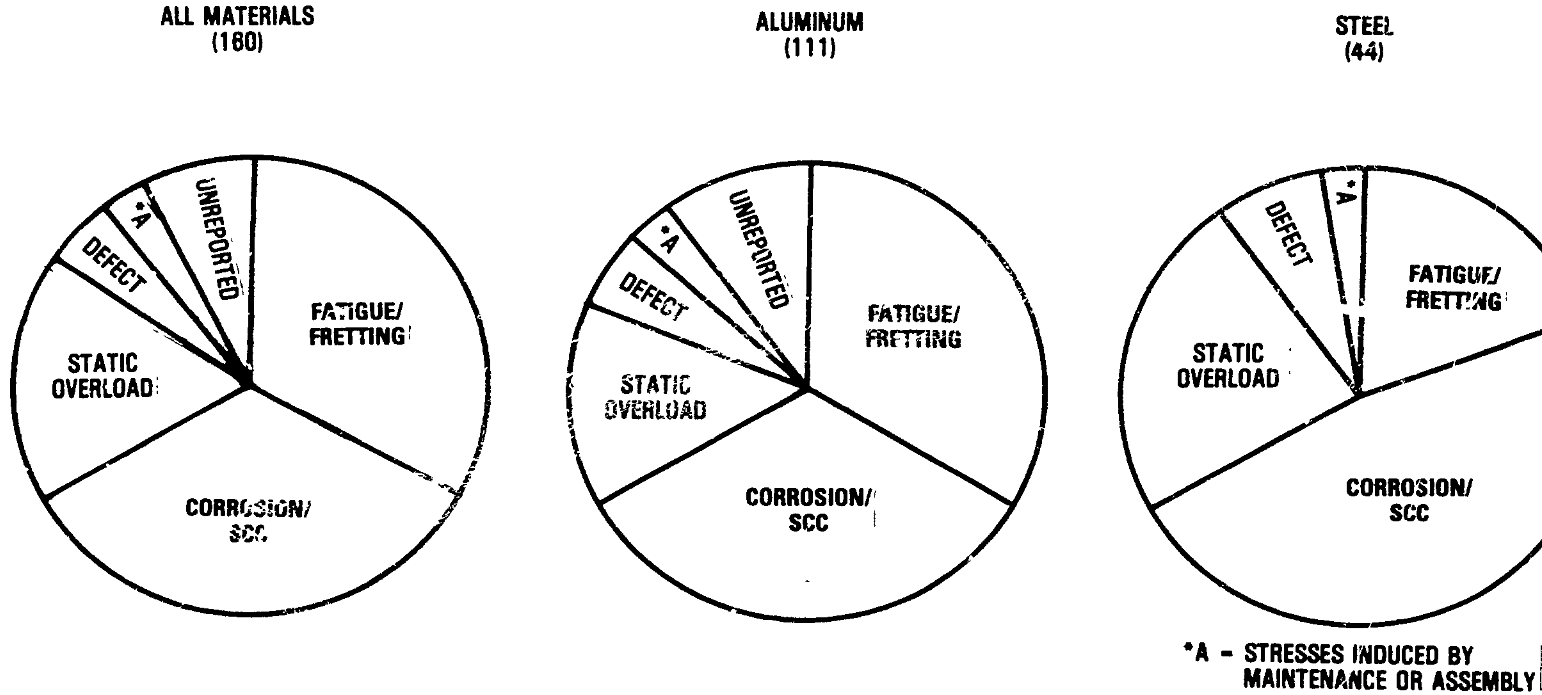


Figure 3-12. Causes of Initial Cracking of Lugs in Service

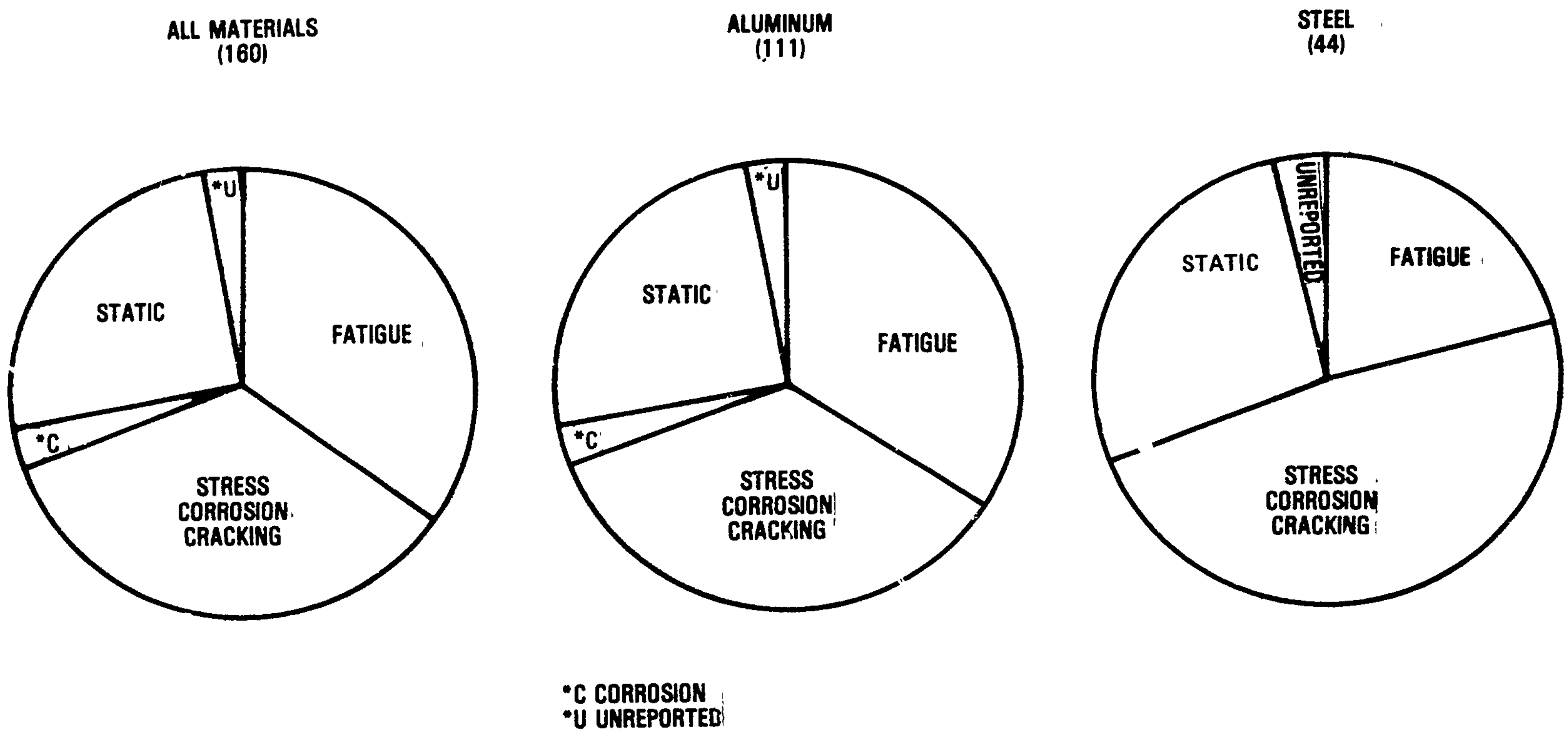


Figure 3-13. Causes of Failure for Lugs in Service

Results of the service cracking data survey indicate that there are three major types of initial cracks common in attachment lugs. As shown in Figure 3-14, the most common is a surface crack in the bore of the hole, which occurs 30 percent of the time in aluminum and 41 percent of the time in steel. One would expect this type of initial crack to evolve into the through-the-thickness crack configuration. The other two most common crack types are a corner crack and a surface crack originating on the specimen face. The surface cracks on the face of the lug often originate near the hole and shortly thereafter become corner cracks.

Initial crack types appear to be related to whether or not the lug is fitted with a bushing or bearing. Of the 160 cracking cases, 61 were reported to have bushings or bearings in the lug hole, 59 did not. (No information about bushings or bearings was readily available for the other 40 cases.) As shown in Figure 3-15, lugs with bushings or bearings tended to have surface cracks in the bore of the hole (43 percent) and very few surface cracks on the lug face (eight percent); whereas lugs without bushings had as many surface cracks on the face as in the bore of the hole (25 percent each).

Figure 3-16 shows how the initial crack type relates to the cause of crack growth/failure. Of the cracks grown by fatigue, corner cracks were most common (38 percent), compared to surface cracks in the hole bore (29 percent) and surface cracks on the lug face (15 percent). In contrast, most cracks grown by stress corrosion cracking were initially surface cracks, either in the hole bore (47 percent) or on the lug face (20 percent) rather than corner cracks (12 percent). Furhtermore, only five percent of static overload failures were initially corner cracks, while 62 percent were initially uncracked.

It is questionable whether the 34 failures initiated by static overload should be included in the survey, because they don't involve pre-existing cracks. Results for the 126 remaining service cracking cases are shown in Figure 3-17. This figure shows again the equally dominant importance of fatigue/fretting and corrosion/stress corrosion as the causes of crack initiation and fatigue and SCC as the causes of growth in lugs. The importance of the three major types of initial cracks is also clear in Figure 3-17, since

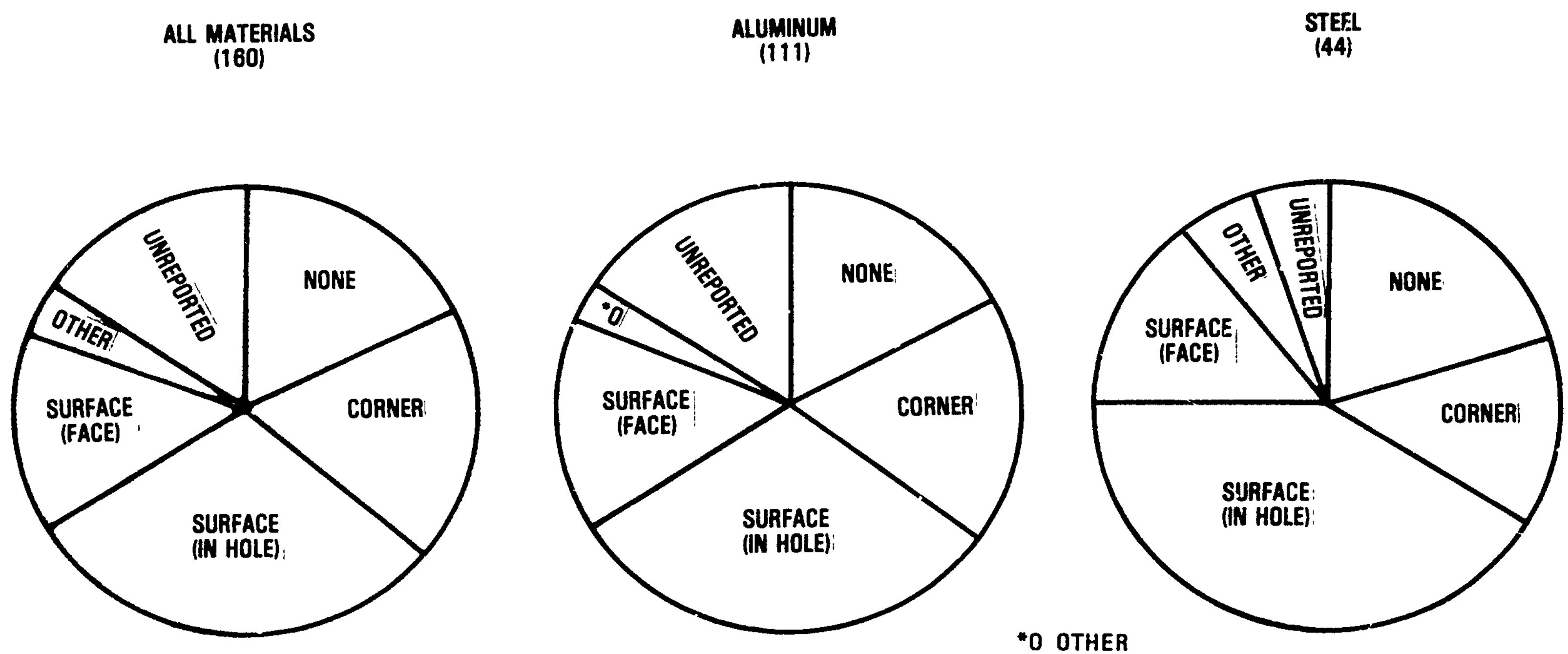


Figure 3-14. Initial Crack Type

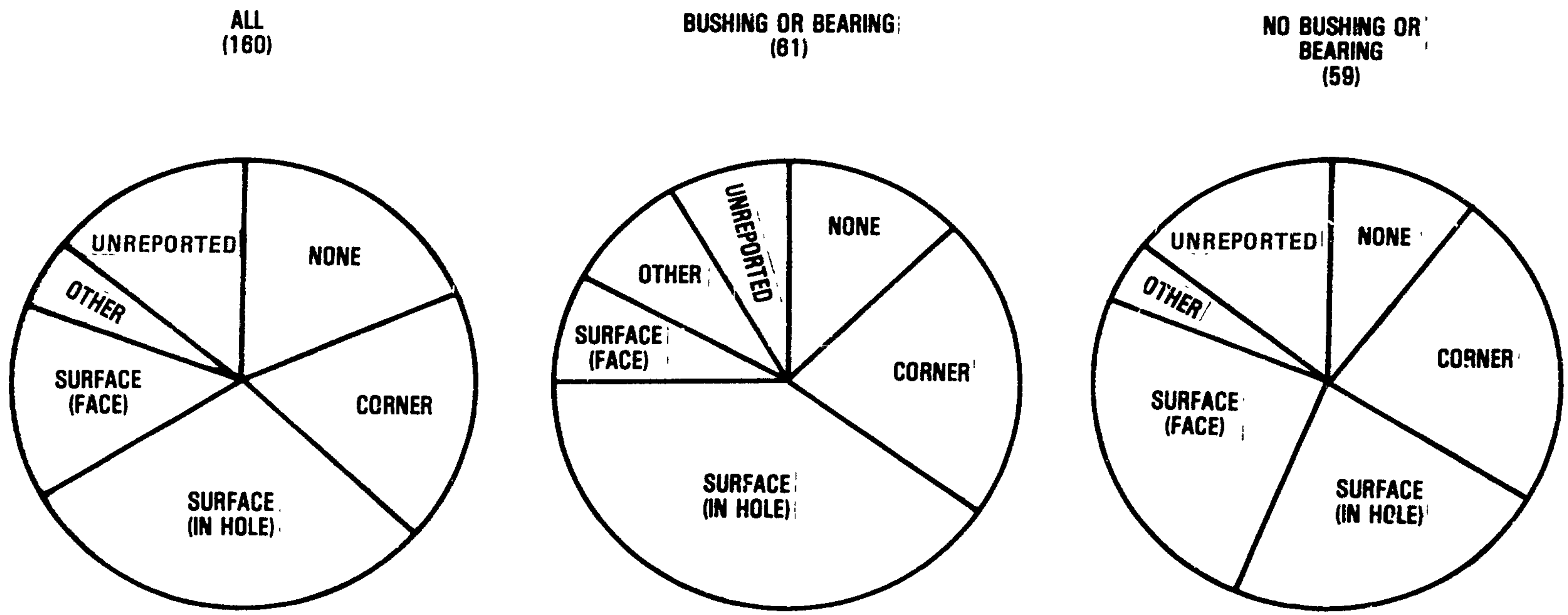


Figure 3-15. Initial Crack Types Related to the Use of Bushings or Bearings

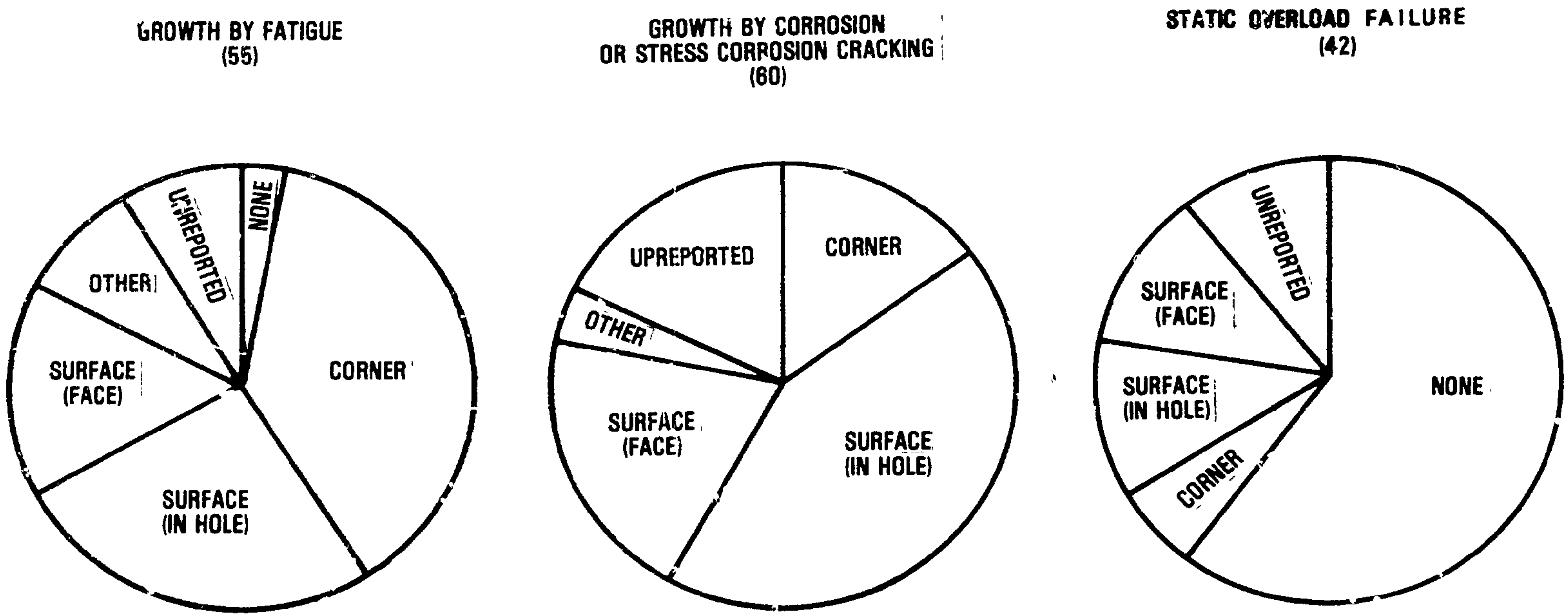


Figure 3-16. Initial Crack Types Related to Cause of Growth/Failure

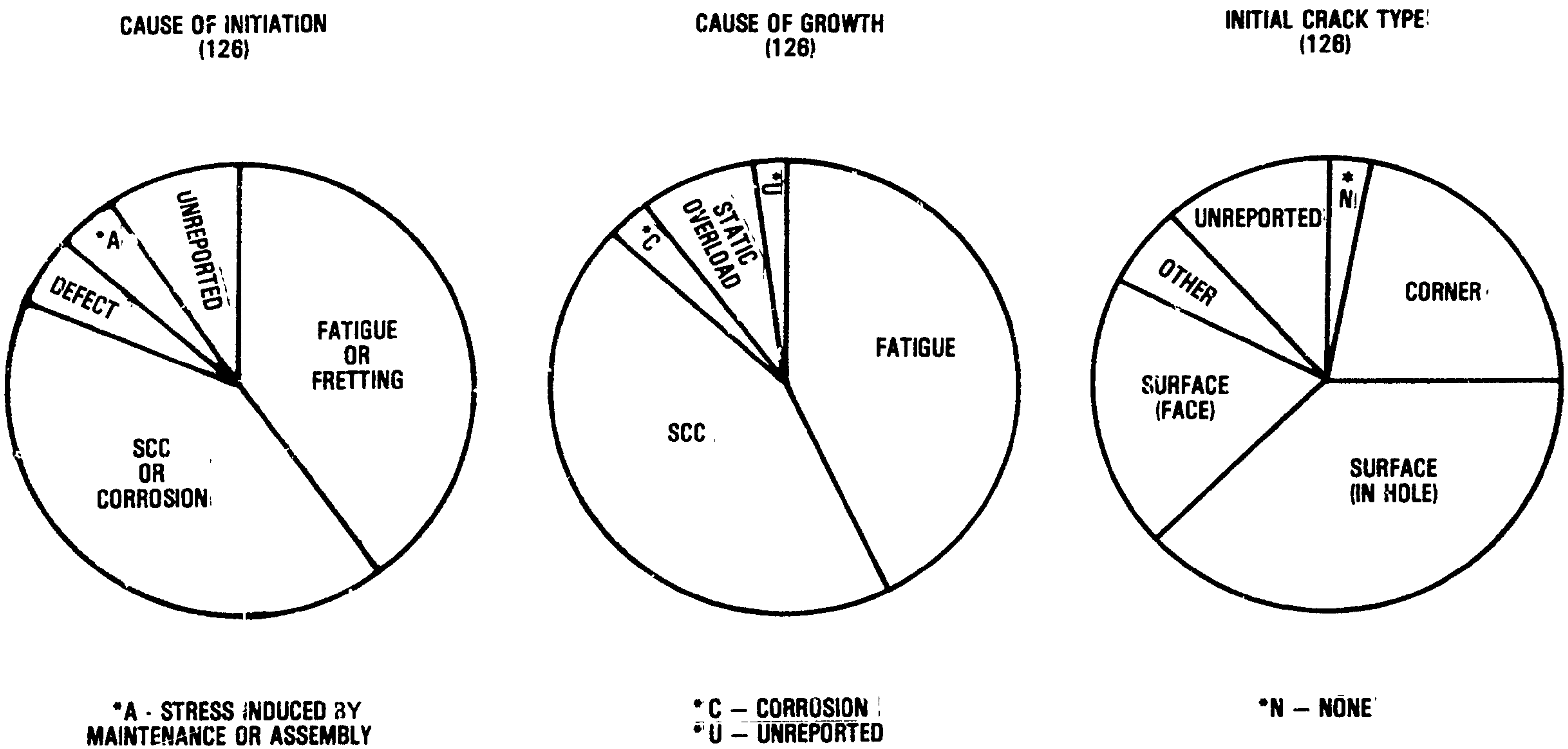


Figure 3-17. Survey Results if Cause of Initiation is not Static Overload

the category "none" (no initial crack) has been eliminated from the crack type chart by excluding cases involving static overload-caused crack initiation.

Figure 3-18 provides a closer look at the 55 cases in which service cracks grew by fatigue crack growth. The figure shows that overwhelmingly, these cracks are also initiated by fatigue. As noted earlier, corner cracks and cracks in the bore of the hole are the two most common initial crack geometries. Flaw multiplicity was examined, and multiple crack origins or nearly-equal cracks on both sides of the lug hole were common, occurring almost as often as a single, one-origin crack. The types of structure represented by these 55 fatigue-failed lugs is also summarized in Figure 3-18. Landing gear structure and lugs from flight-control structure (rudder, elevator, spoiler, leading-edge flap, etc.) are the two most common categories. The survey also included pylon or engine-attach structure, floor hinges on cargo aircraft, landing gear door hinges, wing attach fittings, brake fittings, some bell cranks of undefined function, and a few lugs which may have been non-structural.

If lugs are to be designed for damage tolerance it must be possible to discover the cracks before they reach critical size. A goal is to maximize the difference between the critical crack size and the initial discoverable size. The initial size depends on NDI capability as described in Section 4. Enough information was available from 35 of the fatigue crack growth failure cases to obtain reasonable estimates of critical crack size. The probability plot shown in Figure 3-19 indicates a median critical crack size of $\ell = 0.125$-inch. (The definition of $\ell$ varies depending upon the type of crack, as defined in Figure 3-19.)

A goal of new damage tolerance requirements for lugs would be to eliminate all or nearly all of the service failures represented in Figure 3-19. The types of failures resulting from small critical crack sizes can probably be regarded as design problems, requiring lower stresses or load redundancy to achieve a design that is truly damage tolerant. Those with longer critical cracks can most likely be regarded as inspection problems, requiring more frequent or more reliable NDI.

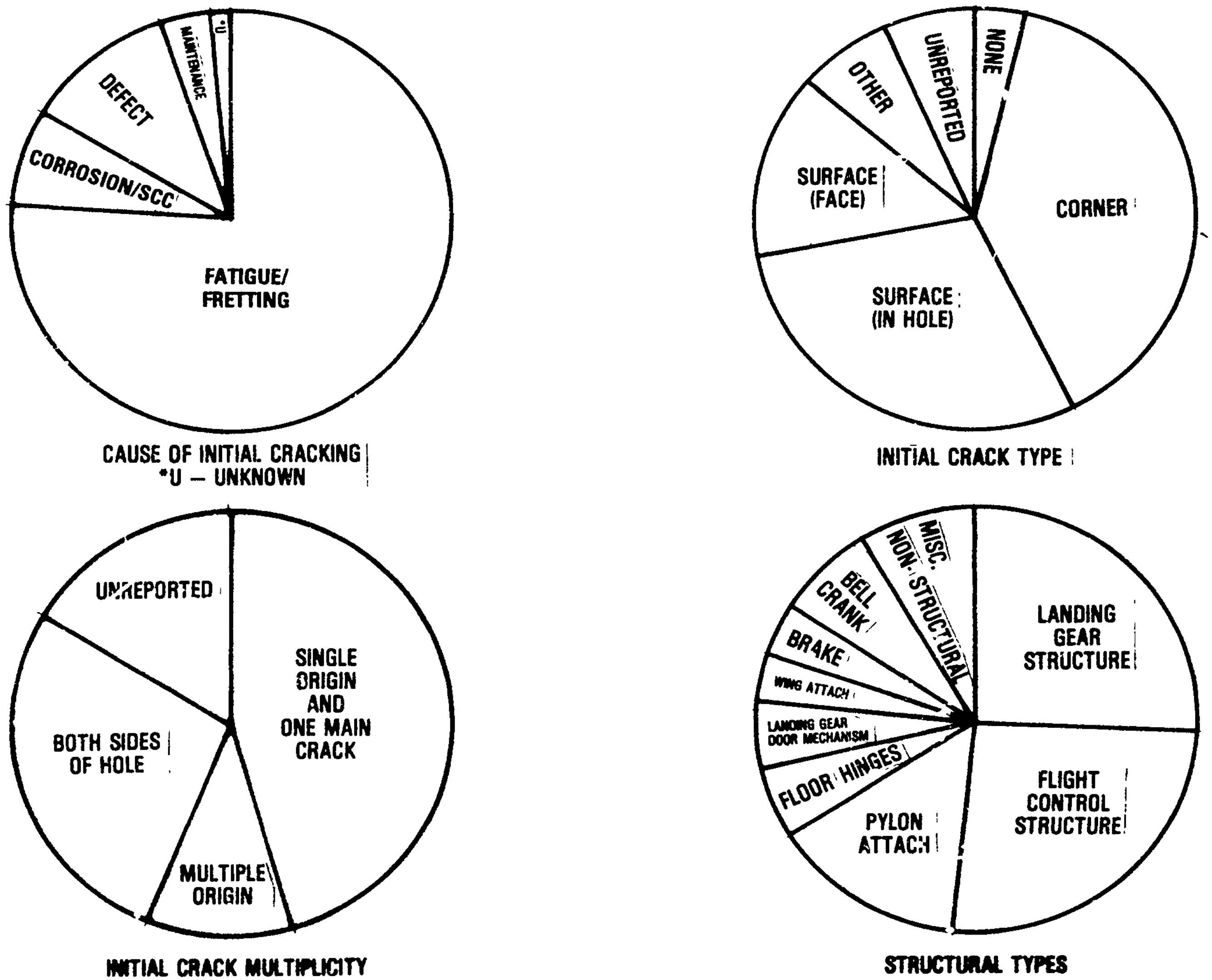


Figure 3-18. Results for 55 Lugs that Failed in Service by Fatigue Crack Growth.

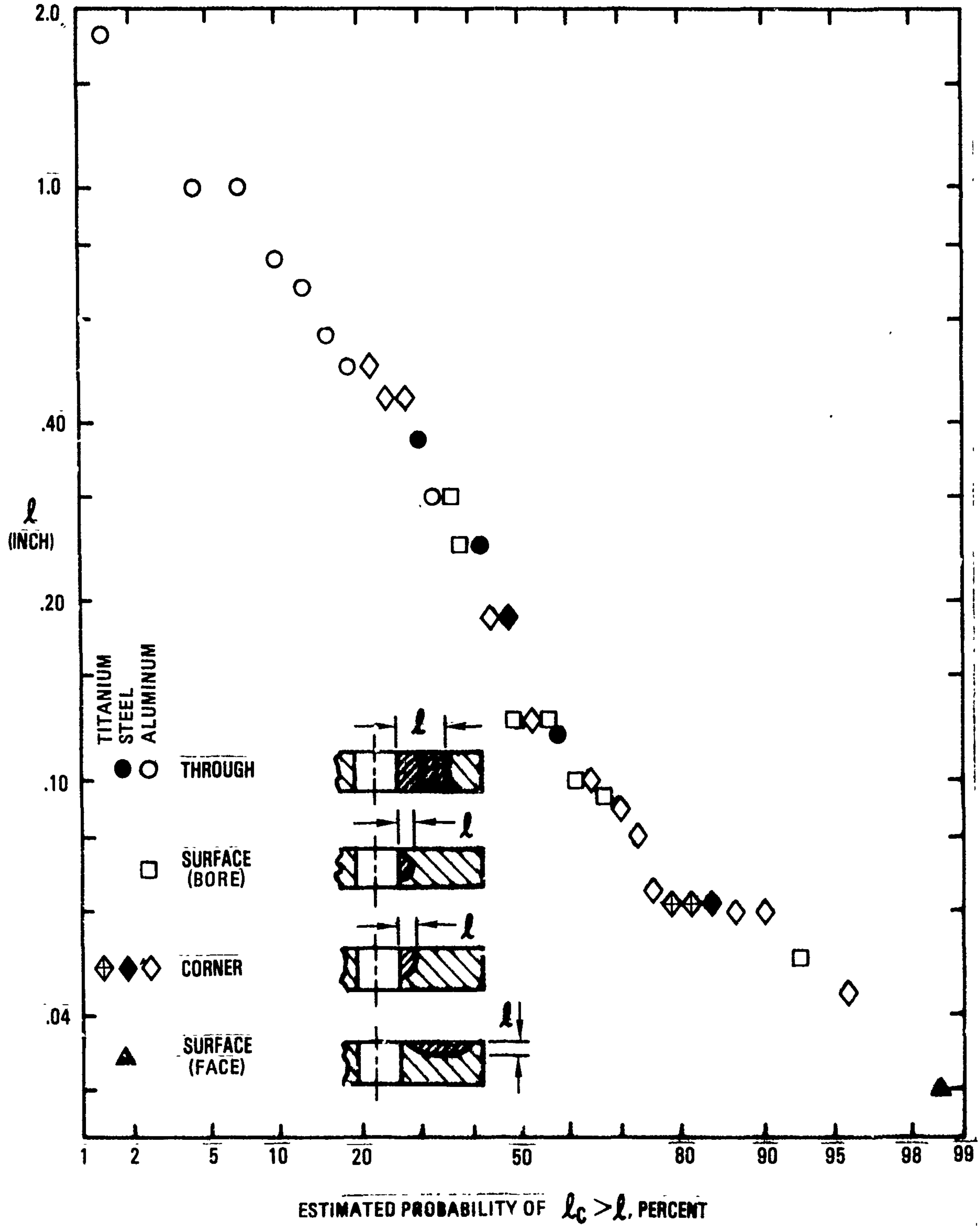


Figure 3-19. Critical Crack Sizes after Fatigue Crack Growth in 35 Service Failed Lugs (Air Force ALC Data Only)

## 3. COMPONENT OR FULL SCALE TESTS

As originally planned, the cracking data survey was to include full-scale and component fatigue test results of lugs as well as service data and lug coupon test data. However, these full-scale and component test data were found to be somewhat ineffective in serving the objectives of the survey. As single test points, they did not provide the valuable statistical information obtained from coupon test results reported in the literature. As test data on the other hand, they were inferior to actual service data in the representation of actual anticipated cracking of aircraft lugs in service. Therefore, a relatively low priority was placed upon obtaining and reviewing data from full-scale fatigue tests of lugs.

Nevertheless, 24 full-scale test results were found for the survey. The results are summarized in Figure 3-20. A good cross section of critical structural applications was represented, including two pylon attachment lugs, four wing-fuselage attachment lugs, six landing gear lugs and six helicopter rotor system lugs. Corner and surface cracks in the bore of the hole were the most common types of cracks found, as in the case of the service cracking fatigue data. Of the 14 cases where multiple cracking information was adequately reported, single and multiple cracking was equally likely, which also was similar to the crack multiplicity data from service fatigue failures shown in Figure 3-18.

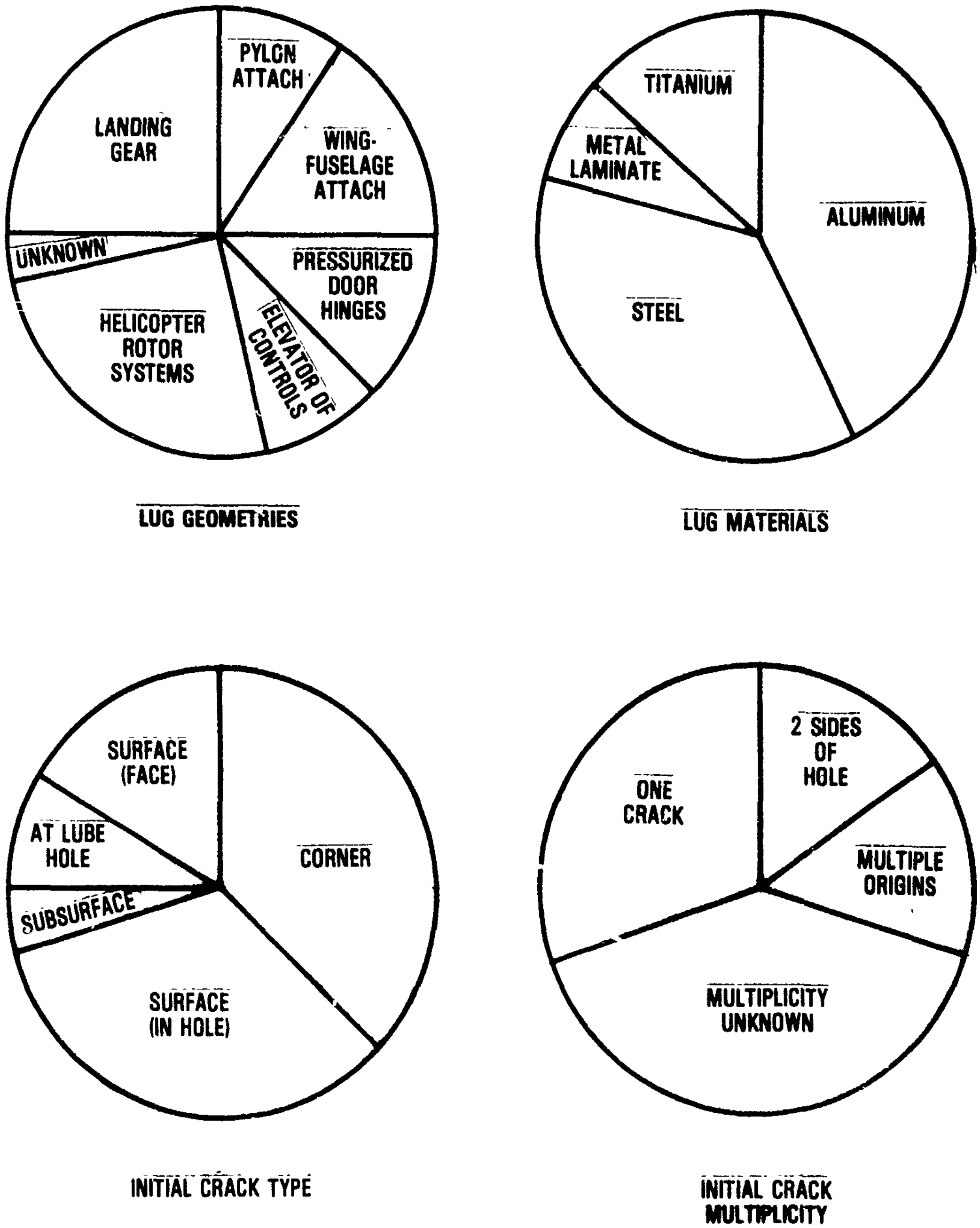


Figure 3-20. Cracking Data Results from 24 Full-Scale Fatigue Test Failures of Lugs

# SECTION IV

## NDI ASSESSMENT

The ability to detect flaws by NDI is necessary for a workable damage tolerance design philosophy. Known capabilities for the detection of flaws in both production and in-service environments allow for the assurance of structural integrity within operating intervals defined by predicted fracture and fatigue behavior. Flaw detection by NDI is probabilistic, however, and it is influenced by a number of factors such as NDI method, material type, part configuration, environment, inspector proficiency, etc. The assignment of values to detection probabilities and flaw sizes in damage tolerance criteria must therefore reflect a careful consideration of numerous influences on the NDI processes.

The objective of this NDI assessment was to seek out and to identify the capability of current NDI techniques in finding flaws in attachment lugs, including the flaw size these techniques are capable of finding.

The following two subsections present the results of this NDI assessment. Brief descriptions of the NDI methods applicable to lugs are given in Section 1. The survey results, conclusions and recommendations relating to initial crack size assumptions for attachment lugs are presented in Section 2.

### 1. NDI METHODS

In this section, the available NDI methods which can be used to detect the flaw in attachment lugs are briefly discussed.

#### 1.1 Dye Penetrant

The principle of the use of dye penetrant is very simple. The component is cleaned and sprayed with a colored or fluorescent dye, which seeps into any open surface cracks. After allowing sufficient time for penetration, excess dye is wiped away and the surface is dusted with developer. The developer acts like blotting paper, and defects are revealed as lines of dye against the white chalky background of the developer.

The method is economical and is widely used. It has sensitivity to a surface crack with surface opening, but the sensitivity diminishes severely for "tight" cracks; i.e., cracks with surface closure, or surface cracks contaminated with foreign material.

### 1.2 Magnetic Particle

The magnetic particle technique is applicable only to ferromagnetic materials. A magnetic flux is induced into the part. The flux in the metal greatly exceeds that in the surrounding air. Any surface or near-surface defect that happens to cut the flux lines will cause flux leakage from the metal and so create an abnormally high field in the air above. This leakage field is detected by the local collection of fine magnetic particles. Surface defects give weak, diffused indications, so the magnetic particle method is usually used to detect only surface defects or cracks. The reliability of crack detection depends on many test parameters, such as induced flux density and orientation, the magnetic properties of the material, the separation of the crack surfaces, the surface condition, and the viewing conditions.

### 1.3 Magnetic Rubber

The magnetic rubber inspection technique is also applicable only to ferromagnetic materials. This method combines the principles of magnetic particle inspection with a novel replicating system. It uses a formulated, room temperature vulcanizing rubber containing ferromagnetic particles. This liquid rubber is catalyzed and poured onto the surface or in the hole to be inspected. A magnetic field is then induced, causing the magnetic particles in the rubber to migrate and concentrate at the location of any flaw. After the rubber has cured, it leaves a replica that can be reliably and easily examined in a convenient lab area with a low-power microscope. The cast impression can be retained for a permanent record. This technique is a sensitive and reliable method for inspecting the inside of very small or threaded holes or hard to reach areas. If it is properly and carefully used, good inspectors may be able to reliably find a crack of 0.010 to 0.020-inch. Human error is reduced and reliability enhanced by having each magnetic rubber replicate inspected separately by two inspectors. The magnetic rubber method maintains sensitivity even for tight cracks.

## 1.4 Eddy Current

When a coil carrying an alternating current is placed near a metal surface, eddy currents are induced at the metal surface. The penetration depth of the eddy currents is determined by the frequency of the current and the magnetic permeability and electrical conductivity of the metal. As the coil is scanned over the metal surface containing a defect within the penetration depth, the flow of eddy currents is distorted and the associated magnetic field changes. This field links the search coil, so the coil senses the defect or crack as a local change in its impedance. The sensitivity of the technique to cracks depends on the surface conditions and homogeneity of the material. It estimates the flaw severity by comparing the magnitude of the response to the response for a standard using a known flaw.

Automatic eddy current appears to be the most reliable technique known for inspecting the flaw in an aluminum lug with no bushing. The probe is automatically advanced along the axis of the hole and rotated, typically about 0.025-inch per revolution. This way the probe covers all locations in the hole, eliminating a major source of human error. With the use of shielded probes, the automatic eddy current method can be used by a skilled inspector to reliably find cracks in the range of 0.025-inch radial depth.

## 1.5 Ultrasonic

Ultrasonic flaw detection uses a piezoelectric transducer radiating a beam of pulsed sound waves into the structure to be inspected. The transducer is scanned over the surface so that the ultrasonic beam searches the interior volume of the structure. Defects (and geometrical features of the component) reflect the incident pulse, returning a greater or lesser amount of energy to the transducer, which also acts as a receiver. After a delay corresponding to the return time of the pulsed signal, a defect echo is detected. Normally, the defect echoes are amplified, rectified, smoothed, and a graph of echo amplitude is displayed on the CRT screen as a function of time.

The ultrasonic method is sensitive for finding subsurface flaws, cracks induced by corrosion pits, and cracks in a bushed hole without removing the bushing.

## 1.6 Radiography

Radiography is another method for detecting subsurface cracks. A source of x-rays or gamma rays is placed on one side of the component and a suitably sensitive photographic film on the other. Flaws are revealed by their lower absorption of x-ray and the consequent increased blackening of the film by rays that have passed through the defect. The sensitivity of this method is poor compared to other NDI methods. Unless the radiation beam strikes the crack almost tangentially, there is negligible differential absorption between rays passing through the crack and those through adjacent sound material and the crack may be undetectable on the film. Furthermore, radiography requires special necessary safety precautions, and is difficult to apply in service in remote or hot environments.

# 2. RESULTS OF THE NDI SURVEY

The original intention of this effort was to survey and compile the available NDI data from the open literature, Lockheed-California and Lockheed-Georgia Companies, and five Air Force Air Logistic Centers. From the trends in these data, a best estimate of flaw size detectability was to be established (both mean values and associated confidence bounds) for current NDI methods, such as penetrant, magnetic particle, magnetic rubber, ultrasonic, eddy current and radiography. From such detectability estimates the estimated probability of detecting a flaw of a particular size, $P_D$, for each NDI technique involved could be calculated, as well as confidence level assigned to that probability. The probability of missing a flaw of a particular size, $P_M = 1-P_D$, during inspection would then be used to determine the initial flaw sizes to be assumed in the damage tolerant design criteria for aircraft attachment lugs.

However, after the extensive discussions with the NDI specialists at Lockheed and the five Air Force Air Logistic Centers, it was realized that there are no statistical NDI data available specifically for lug cracking. To develop meaningful flaw detection reliability data on lug configurations, a rigorous experimental program will be needed. This would require fabrication of a large amount of flawed lug specimens and inspection by many NDI inspectors, and such effort is outside the scope of this program.

Because a vast amount of NDI data is available for fastener holes, the idea was discussed with NDI specialists from the various facilities of translating the probability of flaw detection curves for fastener holes to lug configurations. However, the validity of this translation was found to be controversial. Some NDI specialists expressed the belief that fastener hole data can be used directly for lugs, while others felt uncomforable to do so. Most believed that, with proper probes, the flaw detection capability using automatic eddy current does not depend on hole size. Several felt that the flaw detection reliability in lugs should be better than at fastener holes, because lug inspections are more intensive and concentrated on few potential crack sites.

The general findings of the NDI survey, based on the discussions with NDI specialists, are summarized in the following paragraphs.

Accessibility must be required for lug inspections; otherwise the lug should be designed as noninspectable structure. Disassembly, including removal of bushings, seems to be required to reliably detect very tiny cracks. However, disassembly without subsequent overhaul of the lug may induce more damage than it prevents.

Once the in-service parts are disassembled, multiple inspections make sense, since the cost of inspection tends to be small in comparison to the cost of disassembly, overhaul and reassembly. Multiple or redundant inspections will improve the flaw detection probability, as the discussion and numerical example given in Appendix A indicate. However, multiple inspections may cause schedule delays or personnel management problems. For example, according to one NDI supervisor who was interviewed, individual inspectors may misunderstand the purpose of inspections by multiple inspectors, and the resentments could influence the care they take in their work.

The magnetic particle method is least costly, followed by the penetrant method. For eddy current and ultrasonic methods, the initial investment is expensive, but the subsequent inspections are relatively economical. The magnetic rubber method is expensive, both in manhours and material.

Dye penetrant, manual eddy current, and manual ultrasonic methods will not reliably detect cracks under 0.10-inch in radial length. Radiographic methods tend to be significantly less sensitive. For a lug with a bushing in place, only the ultrasonic or radiographic methods can be used for surface flaws in the hole bore, the most common initial crack geometry for that case (see Figure 3-15 in Section III).

Tight cracks have a strong influence on detectability by some methods, including ultrasonic, visual and penetrant, but not eddy current. Reference [12] found that 0.06-inch deep cracks were usually detectable at fastener holes by use of a portable ultrasonic scanner without disassembly or fastener removal. However, detectability improved to 0.020-inch deep cracks when tension was applied to the specimen to open up the tight cracks. Unfortunately, the application of tension load to a lug during inspection is seldom feasible.

Current depot level inspection procedures in most cases do not seem to be designed to detect cracks under 0.10-inch in length. One NDI method is usually used to do the preliminary inspection, with a second method used as verification when a flaw is indicated. For example, for a preliminary inspection of an aluminum part without a bushing, the penetrant method might be used, and for a steel part without a bushing, the magnetic particle method might be used. If there is an indication of a flaw, either the eddy current or ultrasonic method can be used to do the second inspection. For an attachment lug with a bushing, if the bushing can be easily removed, then the lug can be inspected like the one without a bushing. If it is judged to be impractical to disassemble the part and remove the bushing, then either the ultrasonic or radiography techniques are used in the inspection.

Flaw detection by NDI is probabilistic and is influenced by NDI method, material, part configuration, crack location, orientation and tightness, surface condition including the presence of corrosion products, inspection environment, and inspector proficiency. Of these, inspector proficiency appears to be the most difficult reliability problem. New NDI technology are required which must reduce operator dependency, optimize simplicity, mesh with the work environment, and provide reproducible results.

## 3. RECOMMENDED TARGET SIZES FOR DETECTABLE FLAWS

Despite limited results of this NDI task, the objectives of this contract study require a best possible estimate of the reliably detectable initial flaw size for attachment lugs. Therefore, based upon the subjective information obtained in this NDI assessment task, estimates are made here of flaw sizes for which 90 percent detection probability and 95 percent confidence level can probably be achieved.

Initial flaw size assumptions for aircraft structures in MIL-A-83444 (USAF) "Airplane Damage Tolerance Requirements" are based in part, on what is expected from extensive inspection of structures. The assumed initial corner flaw size at holes and cutouts for slow crack growth structures (0.05-inch radius) could probably be reduced for intensive inspection of lugs. It is recommended that an initial quarter-circular corner crack with a radial length of 0.03-inch be considered for initial manufacturing inspections prior to assembly.

To achieve reliable detection of the small cracks required for lugs, any subsequent inspections would have to be done on the disassembled lug without bushings or bearings or with the bushings removed. If the bushing is removed, a clean-up machine operation will be required before reassembly. Thus, reinspection is feasible when performed in conjunction with a complete overhaul of the lug. In-service inspections of lugs do not in general appear to be feasible, due to the inability to reliably detect the tiny cracks that are usually required.

The current NDI methods with adequate sensitivity appear to be the automatic eddy current method with shielded probes for aluminum lugs, and the magnetic rubber method for steel lugs. Human errors and variations in operator proficiency currently mitigate against reliable detection of such tiny cracks. Some suggested steps include:

- Improved operator training.
- Stiffer operator certification requirements.
- Improved job-longevity incentives (e.g., higher pay ceilings) in order to retain the most highly-skilled NDI specialists.
- Multiple independent inspections.

A thorough verification program paralleling that of Reference [13] will be required to substantiate that these proposed flaw sizes can be detected with 90 percent probability and 95 percent confidence.

## SECTION V

## SUMMARY AND CONCLUSIONS

The cracking data survey and NDI evaluation were carried out to examine the origin causes of cracking in attachment lugs, the causes of failure, the initial crack type, shape, and location, the likelihood of multiple cracking, the critical crack size, and to estimate inspectable flaw sizes for lugs.

### 1. CAUSES OF SERVICE CRACKING AND SERVICE FAILURES

Corrosion/stress corrosion and fatigue/fretting are the two major causes of initial cracking in aircraft lugs in service. Only five percent of the 160 service failures surveyed were traced to initial defects.

Fatigue crack growth and stress corrosion cracking are also the two leading causes of service failures in lugs. Static overload is the third major cause.

These results vary somewhat with material. In aluminum lugs in service, fatigue/fretting and corrosion/stress corrosion are about equally likely causes, both for crack initiation and crack growth. In steel lugs, however, corrosion/stress corrosion is the more frequent cause by a ratio of more than two to one.

In the service data survey, 55 failures resulted from fatigue crack growth. Of these, 76 percent of the cracks initiated by fatigue/fretting and 11 percent from initial defects.

### 2. CRACK TYPE, SHAPE AND LOCATION

The common initial crack types for lugs in service are surface cracks in the bore of the hole, corner cracks, and surface cracks on the lug face near the hole, in that order.

The presence of a bushing or bearing tends to affect the type of initial crack. Surface cracks in the bore of the hole occur more frequently and surface cracks on the lug face less frequently in lugs with bushings or bearings; the reverse was true in lugs without bushings or bearings.

Corner cracks were the most common initial crack type in the 55 service failure cases which failed in fatigue, occurring 38 percent of the time. Corner cracks were also the most common initial crack type in full-scale fatigue tests of lugs. This is in contrast to the cases which failed by stress corrosion, where only 12 percent were corner cracks compared to 47 percent surface cracks in the hole bore.

The predominant shape of corner cracks in lugs can be estimated from lug coupon fatigue data. Coupon data indicate that the ratio of depth "a" to radial length "c" of a corner crack in a lug without out-of-plane bending tends to be about 1.3 or greater.

Criteria for crack location can be evaluated using lug coupon fatigue data. Crack location seems to coincide with either the maximum tangential stress location or the location of the edge of the zone of contact with the pin. These locations can be calculated by finite element analyses, and depend on load direction, fit of the pin or bushing, and to a lesser extent load magnitude.

## 3. CRACK MULTIPLICITY

Multiple-origin cracks and cracks on both sides of the lug hole are common in lug fatigue coupons which have no preflaws and no compressive residual stresses. In the 55 service fatigue failure cases surveyed, multiple-origin cracks and cracking on both sides of the hole occurred almost as frequently as single-origin cracking. Full-scale fatigue test results for 24 lugs show the same trend with respect to flaw multiplicity.

When multiple crack origins along the hole bore coalesce they tend to form a through-thickness crack at a relatively short radial length.

## 4. CRITICAL AND INSPECTABLE CRACK SIZES

The critical crack size was reported for 35 service fatigue failures of lugs in Air Force aircraft structure. The median critical crack size was 0.125-inch radial length. Twenty-five percent of the critical crack sizes were under 0.070-inch radial length.

These small critical crack sizes in lugs seem to require that inspectable flaw sizes must also be small; otherwise the authors expect damage tolerance requirements for lugs will be too costly on lug design.

The problem of establishing reliably detectable flaw sizes for lugs is a statistical problem requiring inspection data. However, statistical NDI data on lugs are not available to establish the detectable flaw size for a required detection probability and confidence level. Therefore, an inspectable flaw size can only be proposed or hypothesized, subject to verification.

The assumed initial flaw size suggested for lugs is a quarter-circular corner crack 0.030-inch in radial length. This size appears feasible for manufacturing inspection and possibly for inspection at time of overhaul of the lug using selected methods, special steps to improve inspector reliability, and perhaps multiple inspections. A thorough NDI verification program is needed to substantiate that this flaw size can be detected with 90 percent reliability and 95 percent confidence.

Multiple cracking is common enough in service and testing of lugs that the possibility of multiple crack origins or equal initial cracks on both sides of the lug hole cannot be ignored in a rational process of creating damage tolerance requirements for attachment lugs.

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# APPENDIX A

## MULTIPLE INSPECTIONS TO ACHIEVE RELIABILITY DESPITE SEMIPROFICIENT INSPECTORS

Flaw detection by NDI is probabilistic, and adequate reliability is particularly difficult to achieve for the very small flaw size required to be detectable in attachment lugs. This appendix describes by means of a mathematical example how multiple inspections can be effective in enhancing inspection reliability.

The probability of missing a crack in a given single inspection can be regarded as the sum of the probability of miss due to inspector-induced human errors ($P_{MI}$), reliability of the NDI method ($P_{MM}$), difficulties with the particular cracked part ($P_{MP}$), difficulties associated with the environment in which the inspection is done ($P_{ME}$), and synergistic effects from combinations of these factors ($P_{MS}$):

$$P_M = P_{MI} + P_{MM} + P_{ME} + P_{MP} + P_{MS} \tag{A1}$$

Reference [14] points out that operator proficiency is a major stumbling block to reliability of inspection. This implies that the $P_{MI}$ term can be relatively large.

Suppose two inspectors without knowledge of each other's results, use the same method in the same laboratory to inspect the same part. If their individual human error probabilities are $P_{MI}^{(1)}$ and $P_{MI}^{(2)}$, then the probability that both will miss the crack is reduced to

$$P_M = \left(P_{MI}^{(1)} \times P_{MI}^{(2)}\right) + P_{MM} + P_{ME} + P_{MP} + P_{MS} \tag{A2}$$

Now a numerical example will be devised to put numbers to this and examine the benefits of multiple inspections. Assume that the method and environment are adequate to achieve 90 percent probability of detecting the required crack, provided the human error can be somewhat optimized. This requires that

$$P_{MM} + P_{ME} + P_{MP} + P_{MS} < 0.10 \tag{A3}$$

Assume for this example that

$$P_{MM} + P_{ME} + P_{MP} + P_{MS} = 0.08 \tag{A4}$$

Now consider a population of 4 inspectors with the following human error probabilities:

$$\begin{aligned} P_{MI}^{(1)} &= 0.03 \qquad & P_{MI}^{(3)} &= 0.10 \\ P_{MI}^{(2)} &= 0.05 \qquad & P_{MI}^{(4)} &= 0.20 \end{aligned} \tag{A5}$$

Using Equations (A1), (A4) and (A5), the total probability of each inspector missing the crack can be calculated. The results are

$$\begin{aligned} P_{M}^{(1)} &= 0.11 \qquad & P_{M}^{(3)} &= 0.18 \\ P_{M}^{(2)} &= 0.13 \qquad & P_{M}^{(4)} &= 0.28 \end{aligned} \tag{A6}$$

Note that none of the four inspectors can achieve the required 90 percent success probability, and for operators (3) and (4) the reliability is obviously very low.

Now suppose that any two of these inspectors, without knowledge of each other's results, use the same method in the same laboratory to inspect the same part. Using Equations (A2), (A4) and (A5), the probability $P_M^{(i,j)}$ can be calculated that both inspectors i and j will miss the crack:

$$\begin{aligned} P_{M}^{(1,2)} &= 0.0815 \qquad & P_{M}^{(2,3)} &= 0.0850 \\ P_{M}^{(1,3)} &= 0.0830 \qquad & P_{M}^{(2,4)} &= 0.0900 \\ P_{M}^{(1,4)} &= 0.0860 \qquad & P_{M}^{(3,4)} &= 0.1000 \end{aligned} \tag{A7}$$

Thus, with double "semi-independent" inspections, any pairing of these inspectors would achieve or surpass the required 90 percent detection probability. Comparison of Equations (A6) with Equations (A7) shows the advantage of double inspections over single inspections for the given example.